Muon Acceleration for Neutrino Factory and Muon Collider

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NUFACT 15
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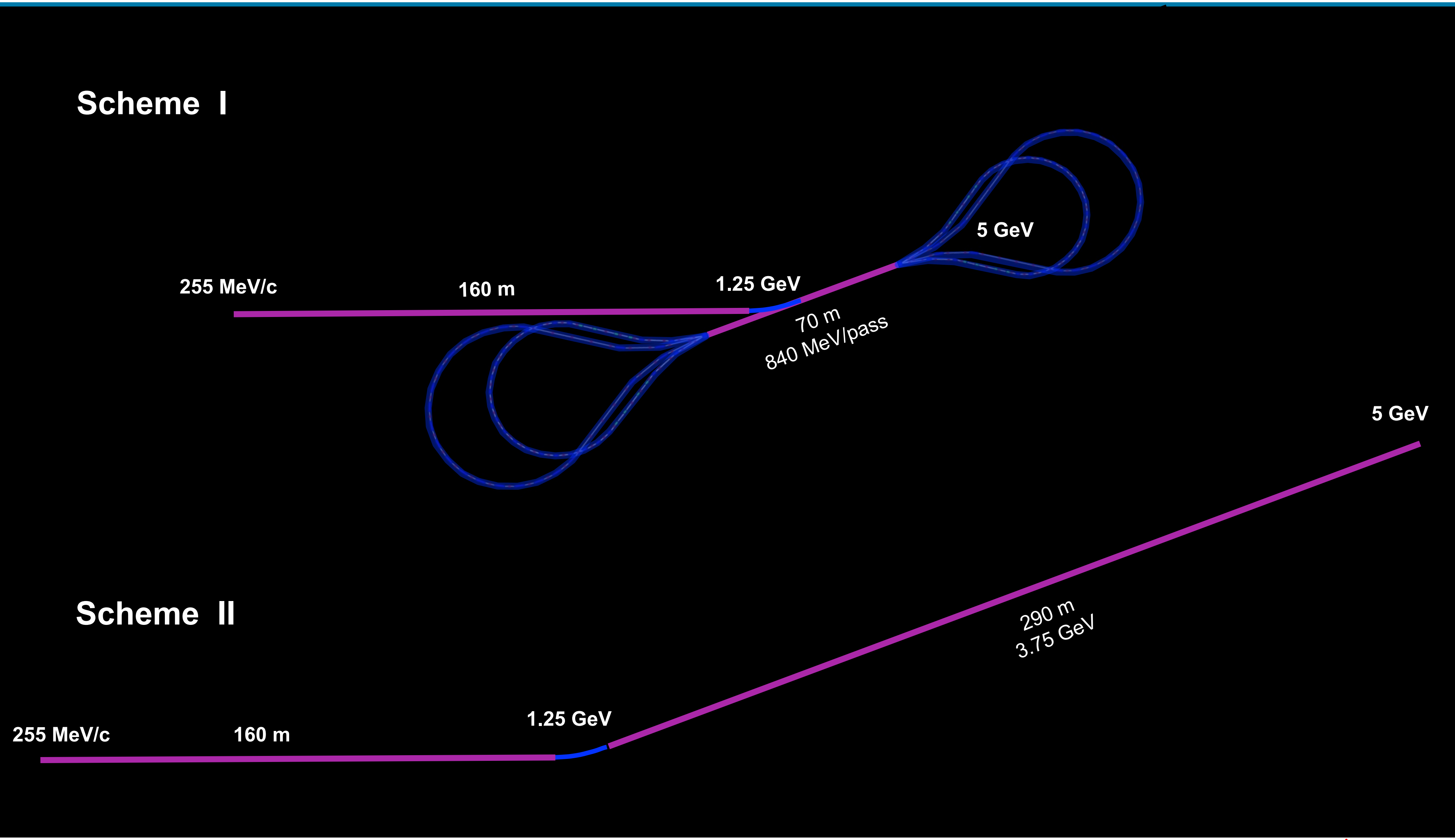
Overview

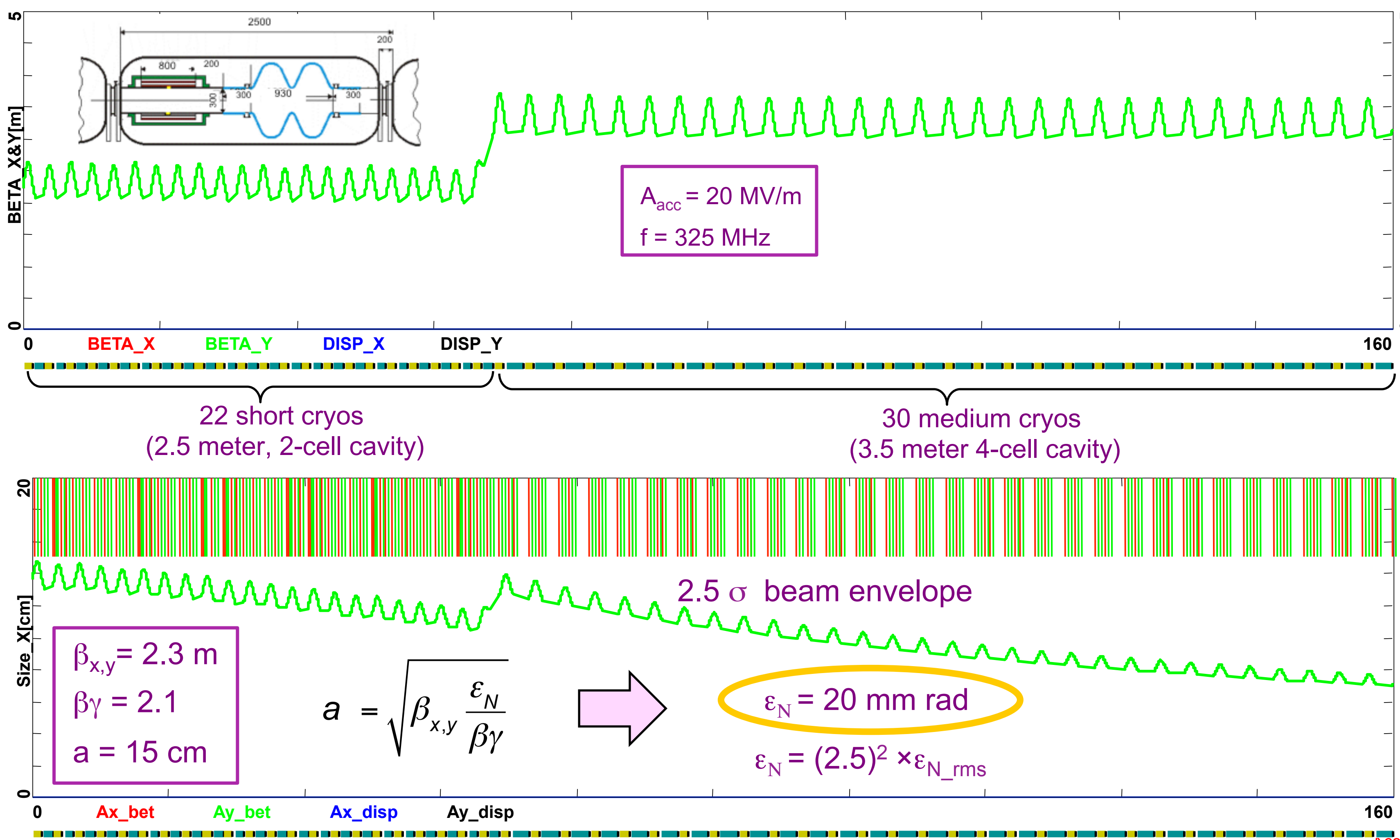
- Cost effective schemes for accelerating muon beams for a stagable, 5 GeV Neutrino Factory (NuMAX)
  - SRF efficient design based on multi-pass (4.5) Dogbone RLA
  - Exploration of dual-use (H^- and muons) linac concepts
- Reducing the cost while maintaining performance through exploring interplay between the cooling systems and the acceptance of the accelerator
- Significant groundwork (schemes and building blocks) was already laid by the IDS-NF efforts and by MASS
- Optimize RLA scheme for Higgs Factory and beyond (MC):
  - Number of passes (beam loading)
  - RLA with multi-pass arcs

NuMAX Acceleration – Design Options



Initial 325 MHz Linac – Transverse Acceptance

p = 255 MeV/c



A_{acc} = 20 MV/m
f = 325 MHz

$\beta_{x,y}$ = 2.3 m
$\beta\gamma$ = 2.1
a = 15 cm

$$a = \sqrt{\beta_{x,y}\frac{\varepsilon_N}{\beta\gamma}}$$

ε_N = 20 mm rad

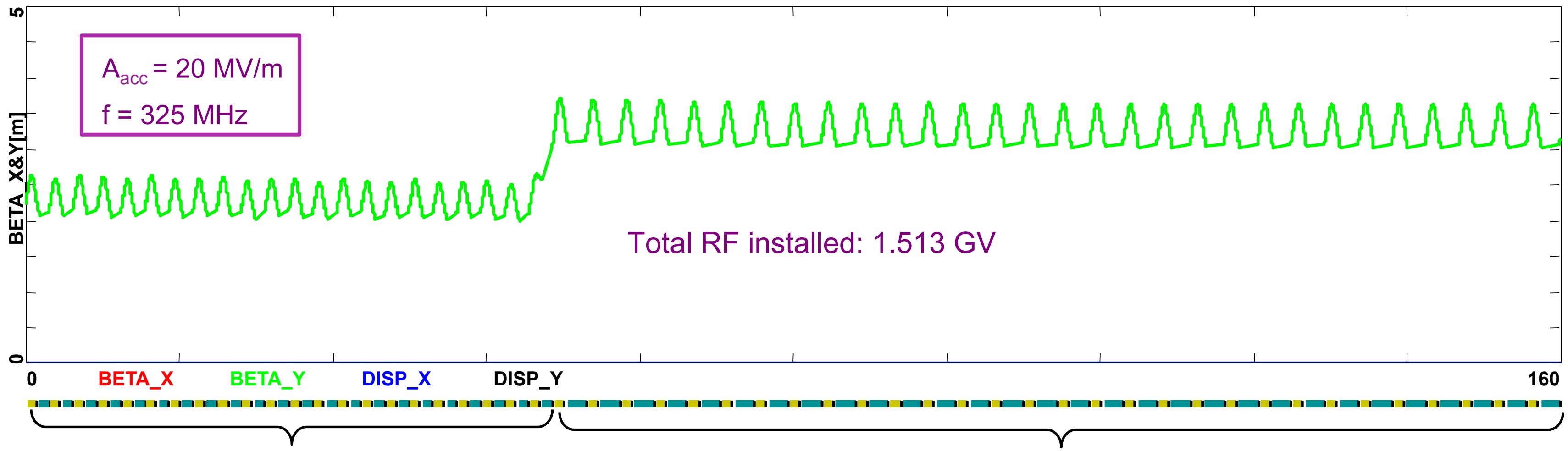
$\varepsilon_N = (2.5)^2 \times \varepsilon_{N\_rms}$

Initial Linac – Longitudinal Profile

p = 255 MeV/c

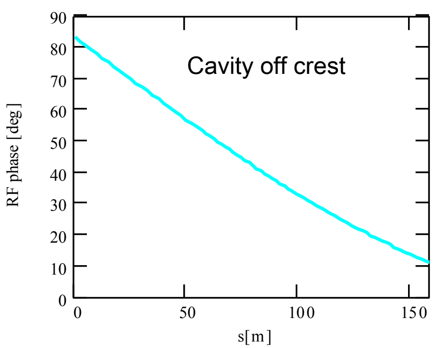
beta functions

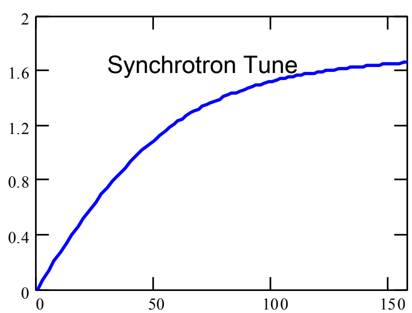
1250 MeV

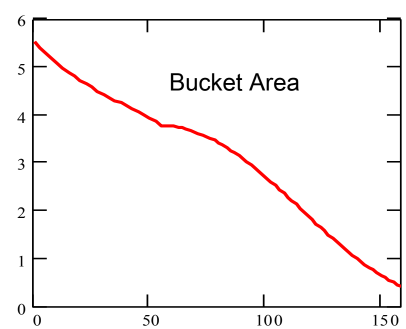


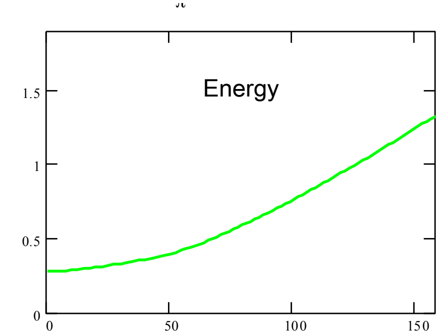
22 short cryos
(2.5 meter, 2-cell cavity)

30 medium cryos
(3.5 meter 4-cell cavity)







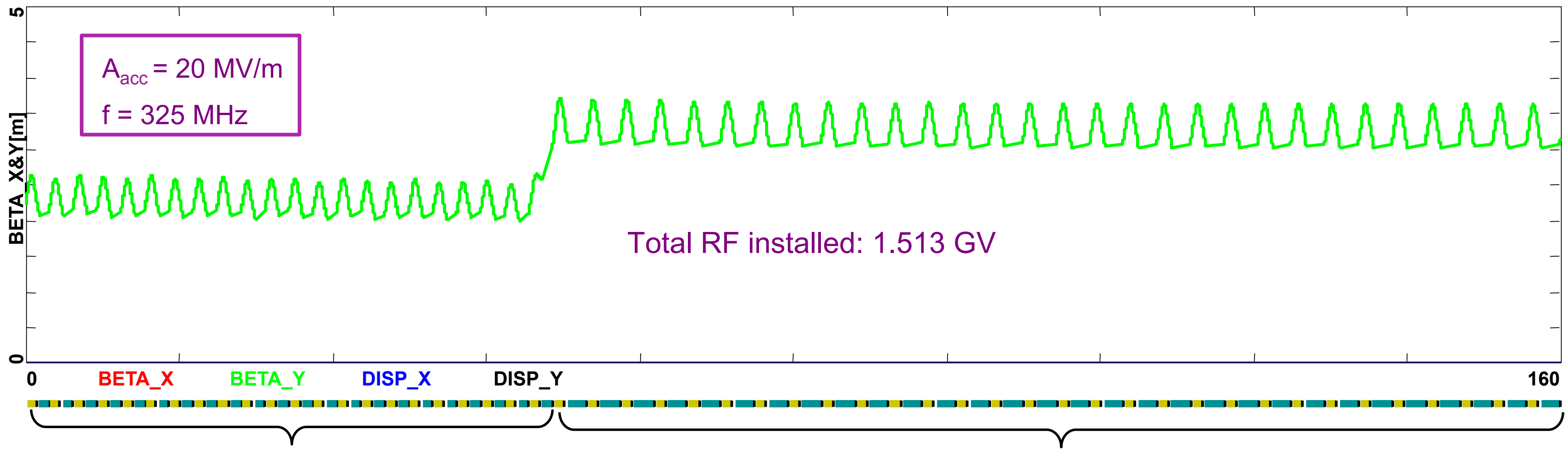


Initial Linac – Longitudinal Acceptance

p = 255 MeV/c

beta functions

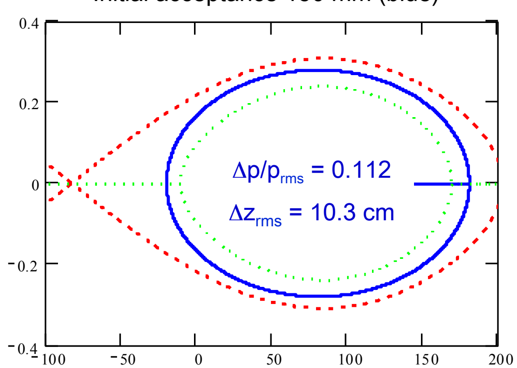
1250 MeV



22 short cryos
(2.5 meter, 2-cell cavity)

30 medium cryos
(3.5 meter 4-cell cavity)

Initial acceptance 150 mm (blue)

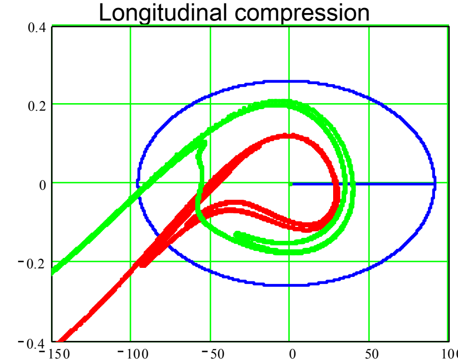


Longitudinal acceptance

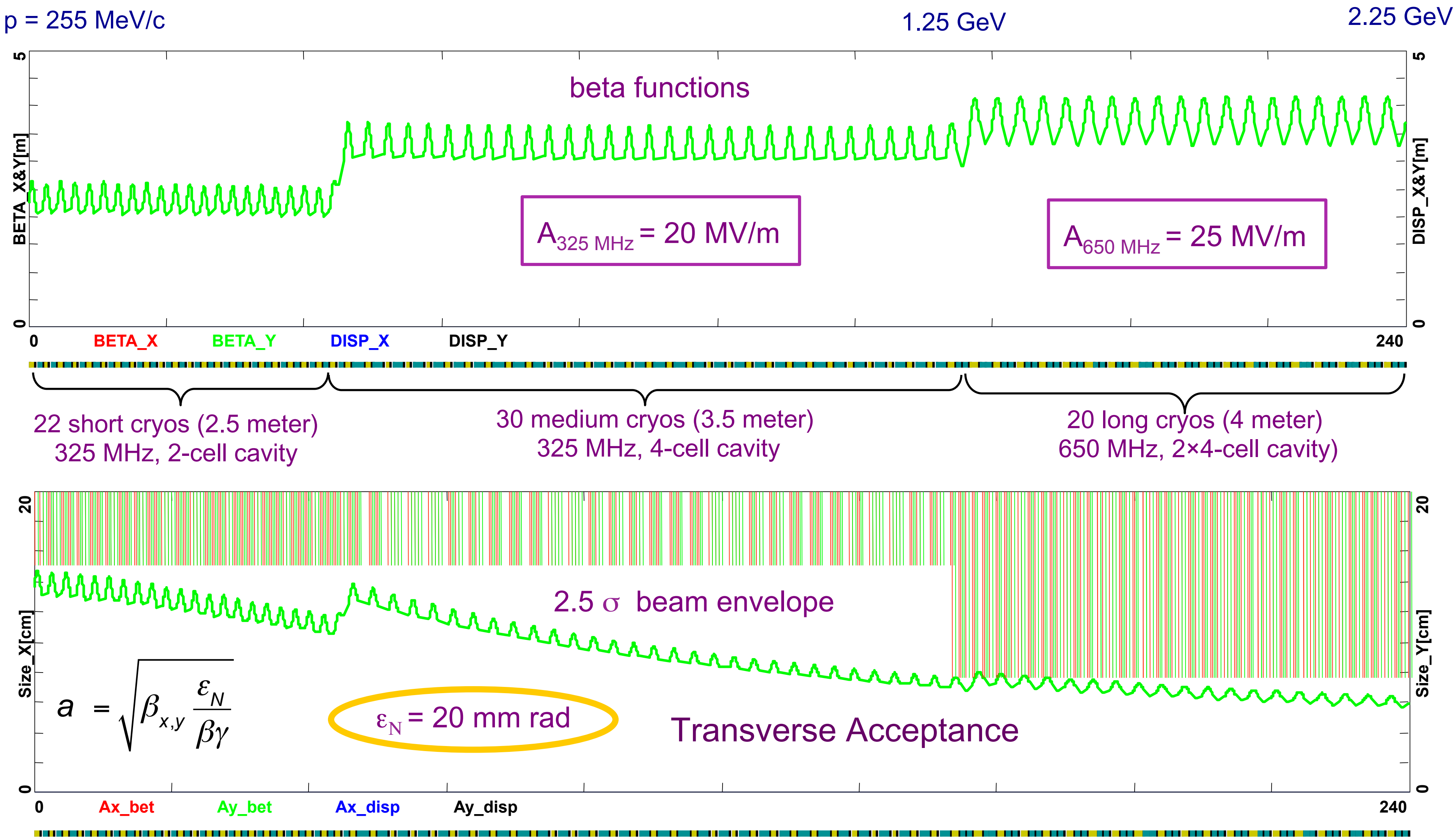
ε_{Long}= 150 mm

$\varepsilon_{Long} = (2.5)^2 \times \varepsilon_{Long\_rms}$

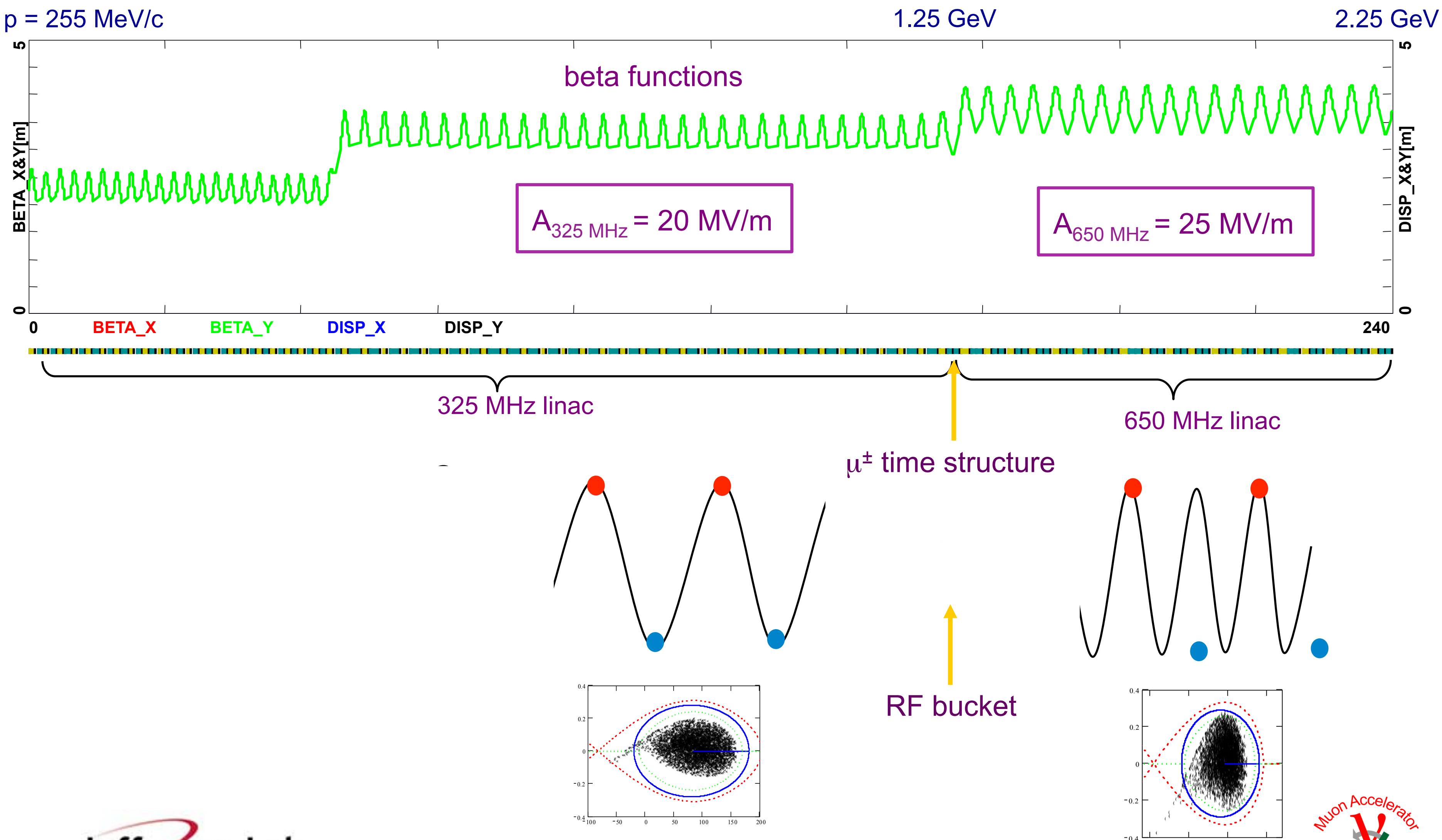
Longitudinal compression



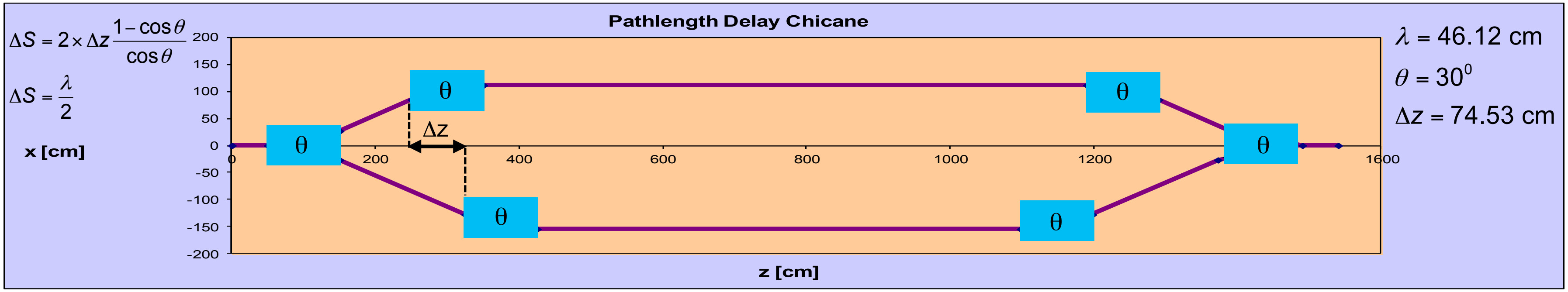
325 MHz – 650 MHz Linac



325 MHz – 650 MHz Transition

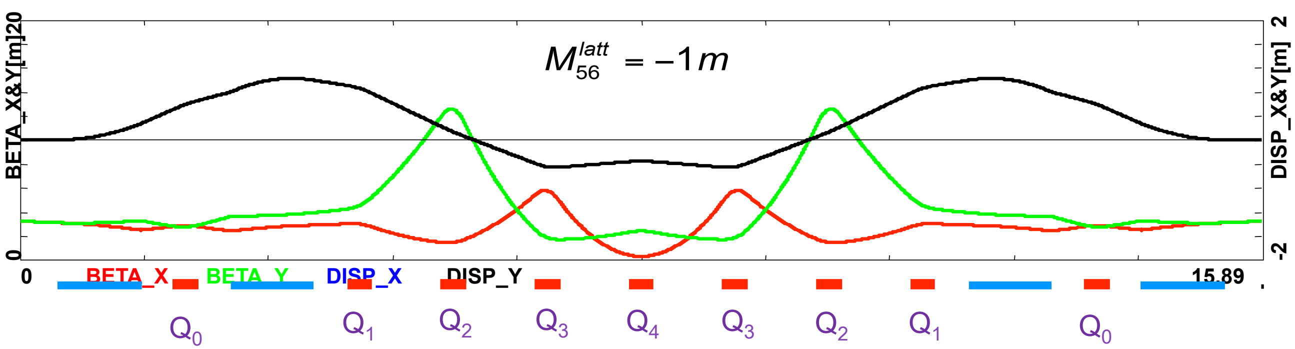


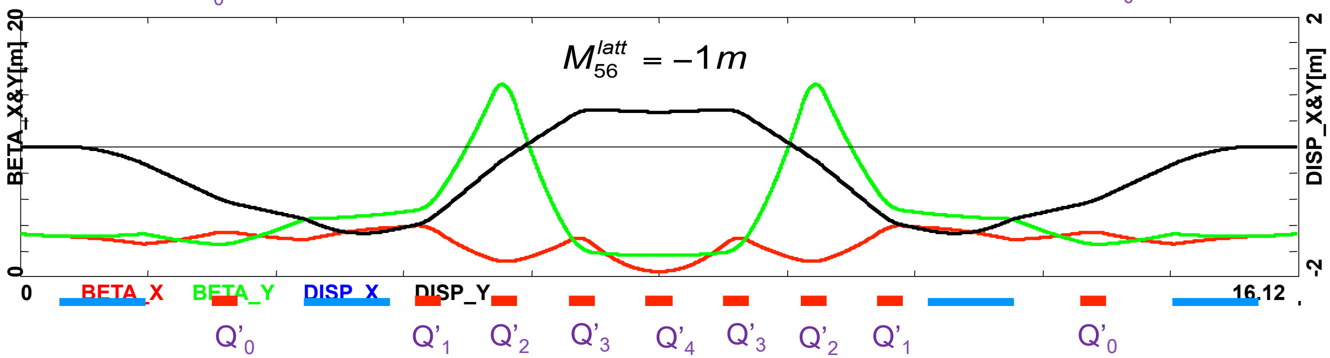
Delay/Compression Chicane



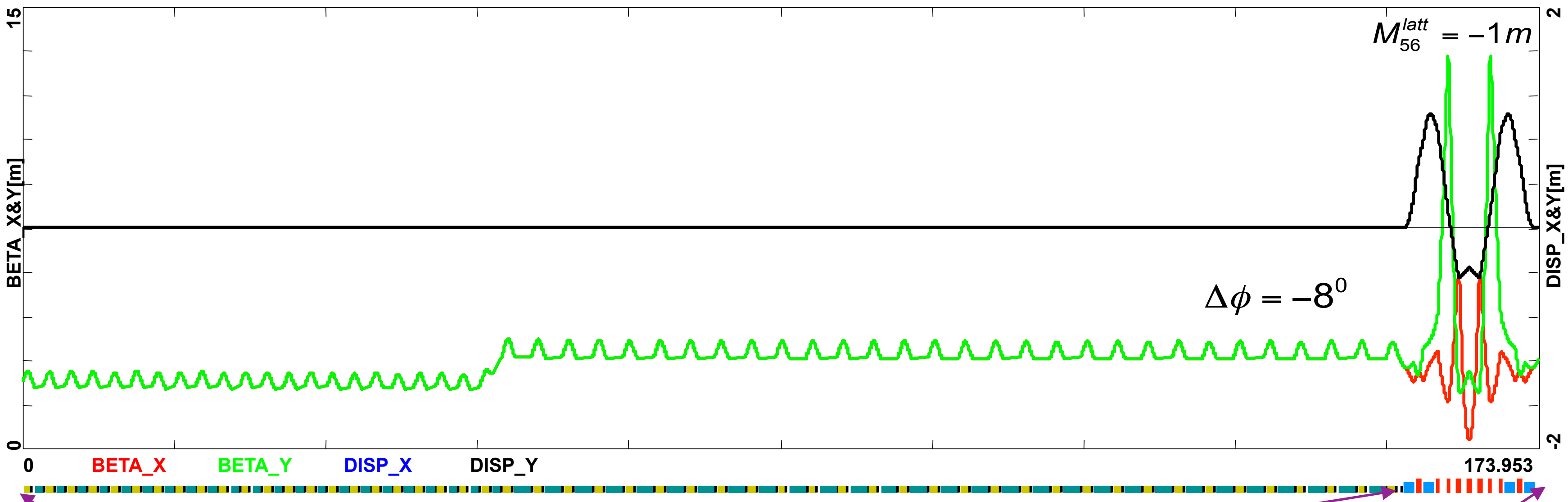
5 free parameters needed to match: 2 betas + 2 alphas + disp.

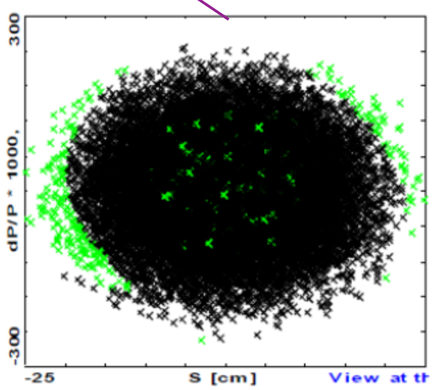
$$M_{56}^{latt} = \int \frac{D}{\rho} ds$$

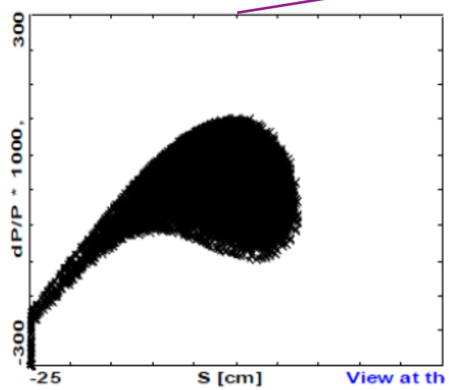


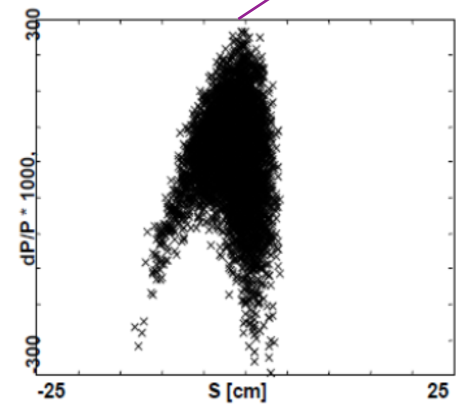


Longitudinal Compression with M_{56}

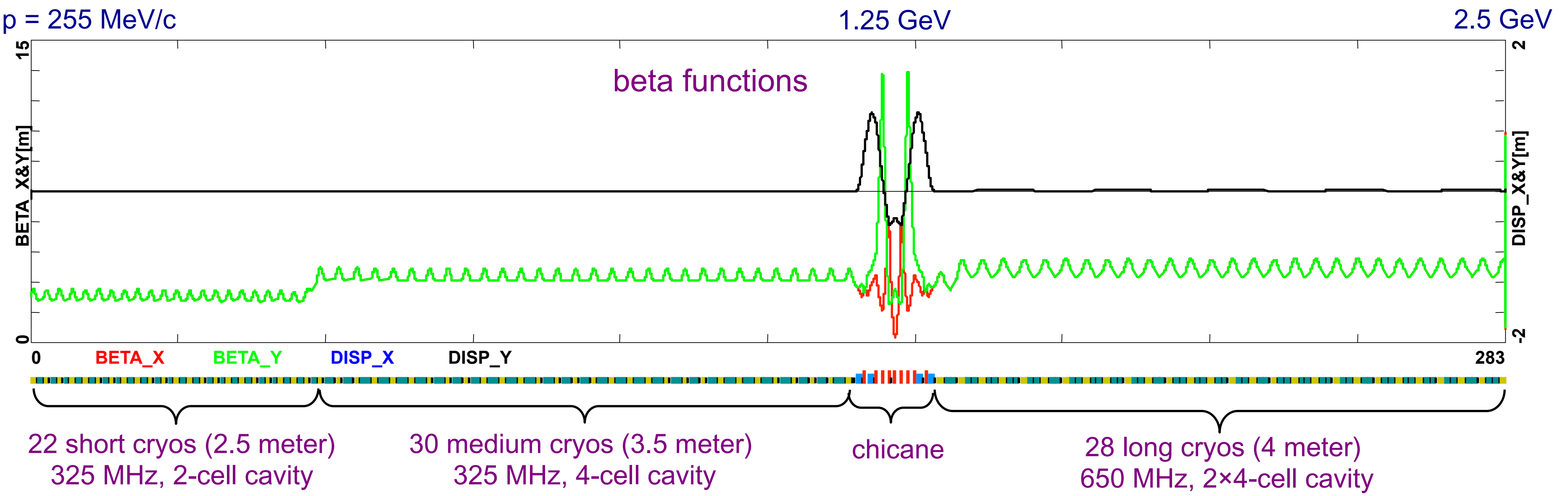


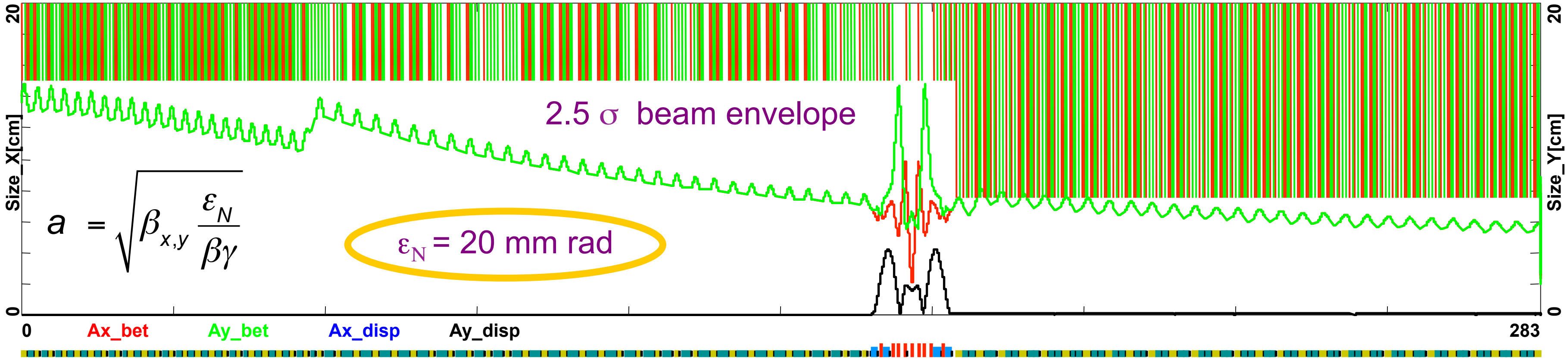






325 MHz – 650 MHz Linac



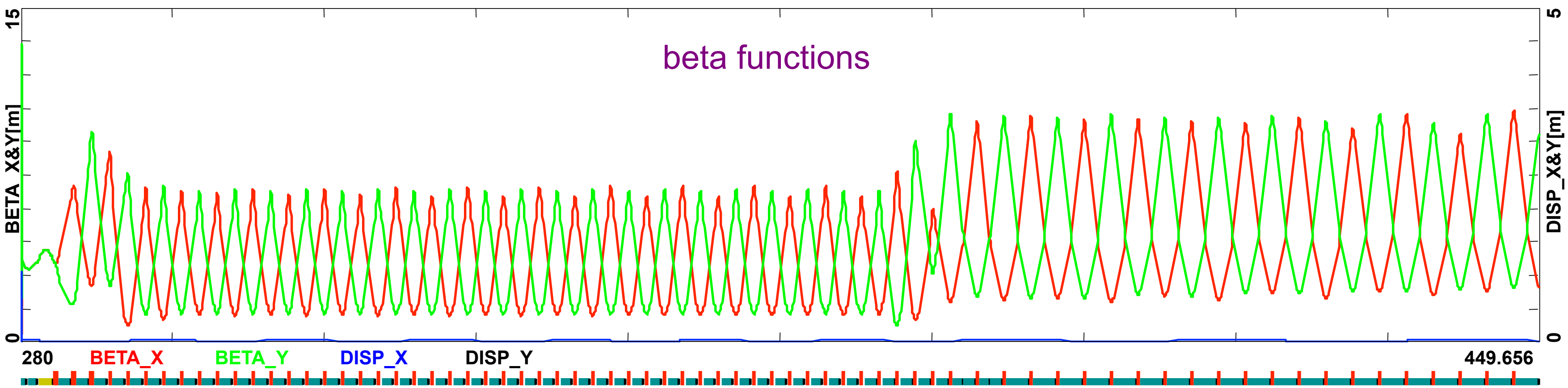


$$a = \sqrt{\beta_{x,y} \frac{\varepsilon_N}{\beta\gamma}}$$

ε_N = 20 mm rad

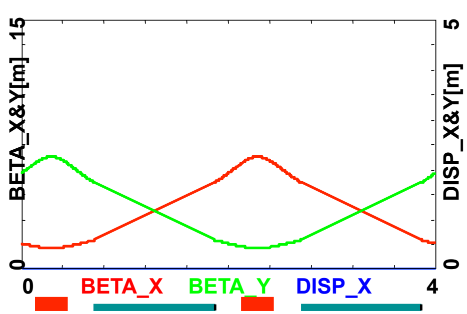
650 MHz FODO Linac

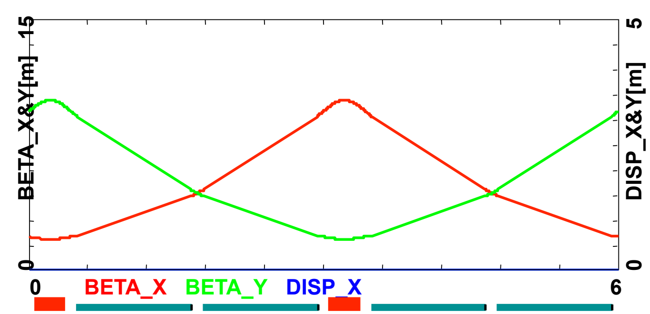
2.5 GeV 3.8 GeV 5 GeV



25 FODO cells (4 m)
2×4-cell cavity

11 FODO cells (6 m)
4×4-cell cavity

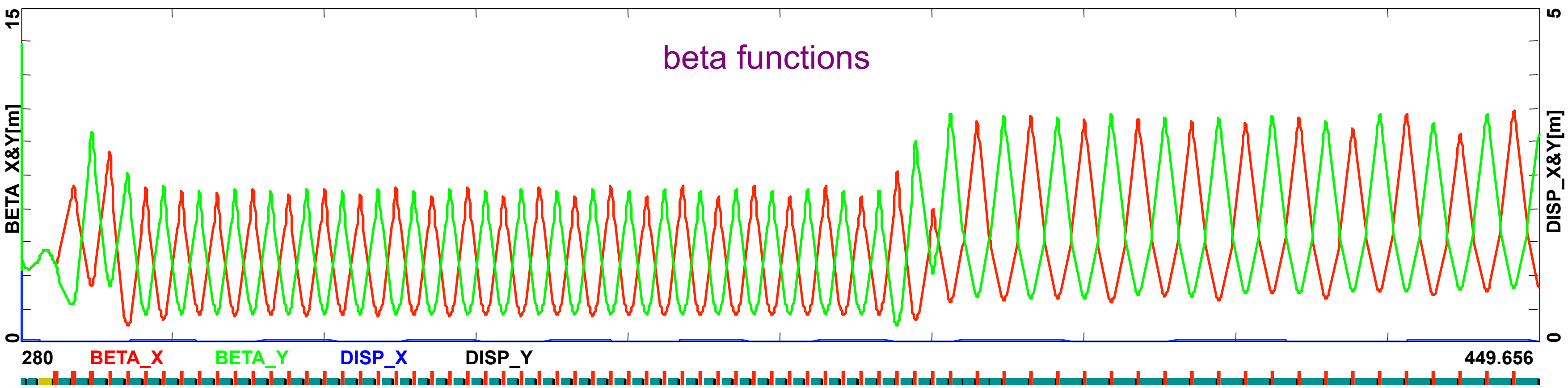




650 MHz FODO Linac

2.5 GeV   3.8 GeV   5 GeV

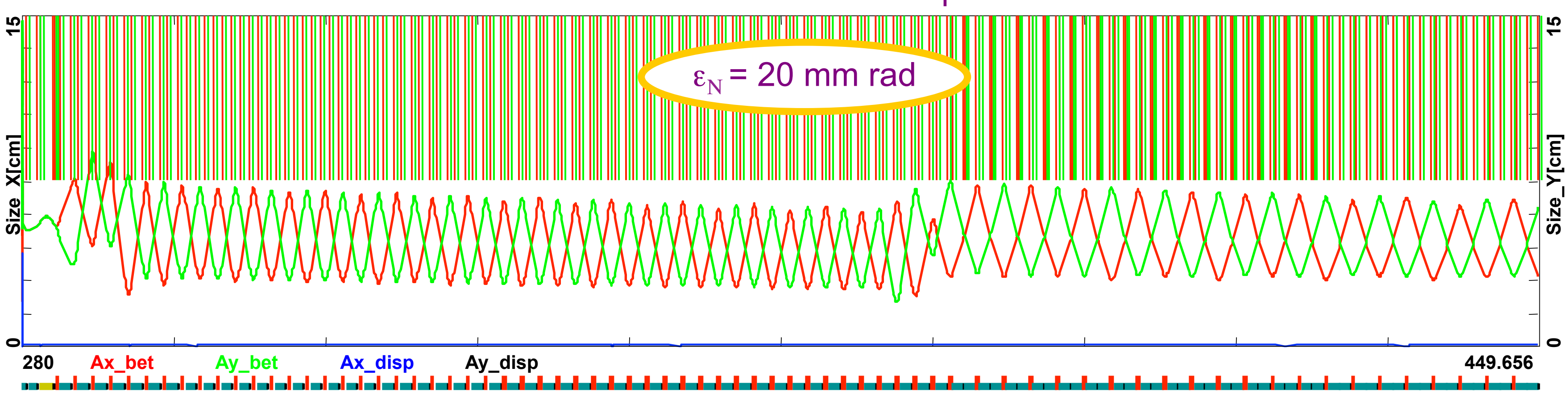
beta functions



25 FODO cells (4 m)

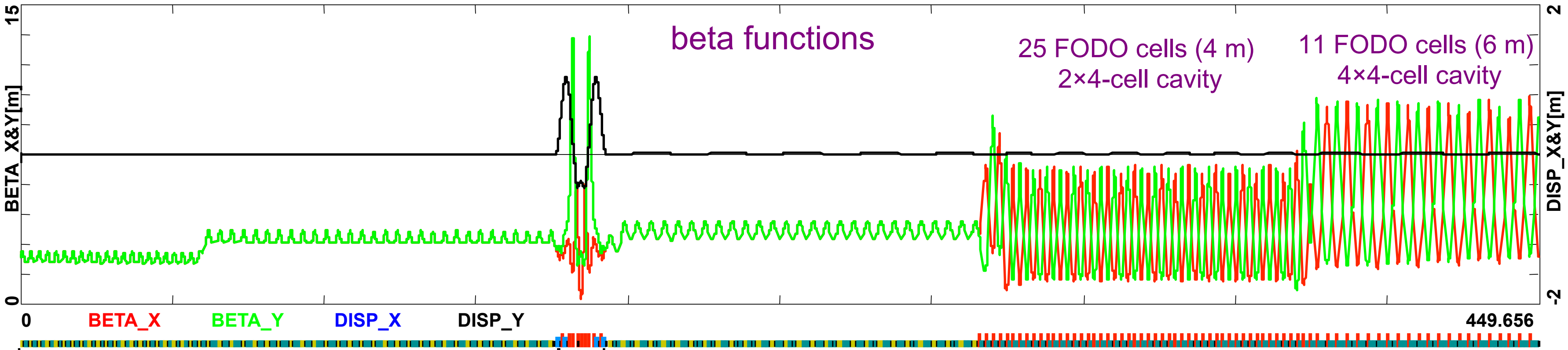
11 FODO cells (6 m)

2.5 σ beam envelope



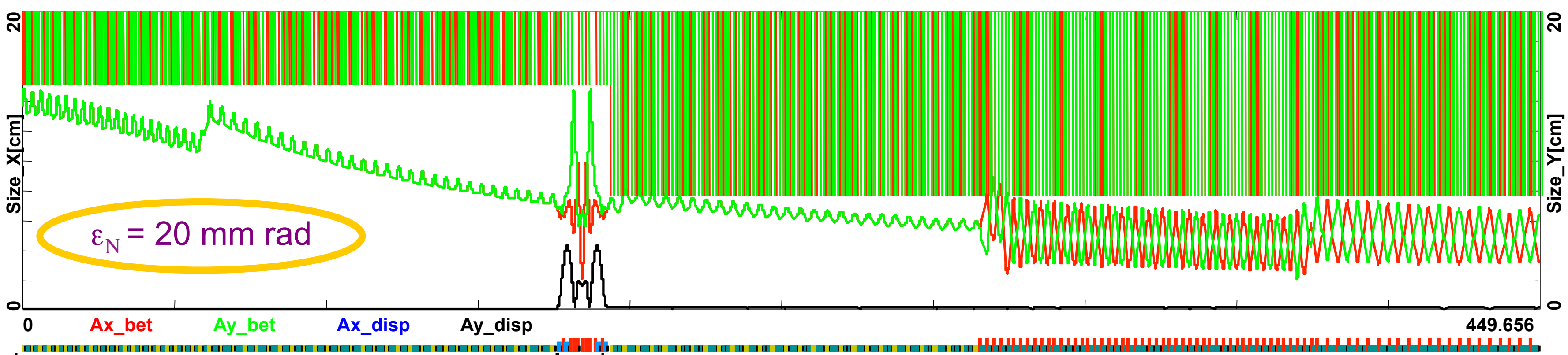
325 MHz – 650 MHz Linac

p = 255 MeV/c | 1.25 GeV | 2.5 GeV | 3.8 GeV | 5 GeV



325 MHz muon linac | chicane | 650 MHz dual-use linac

2.5 σ beam envelope

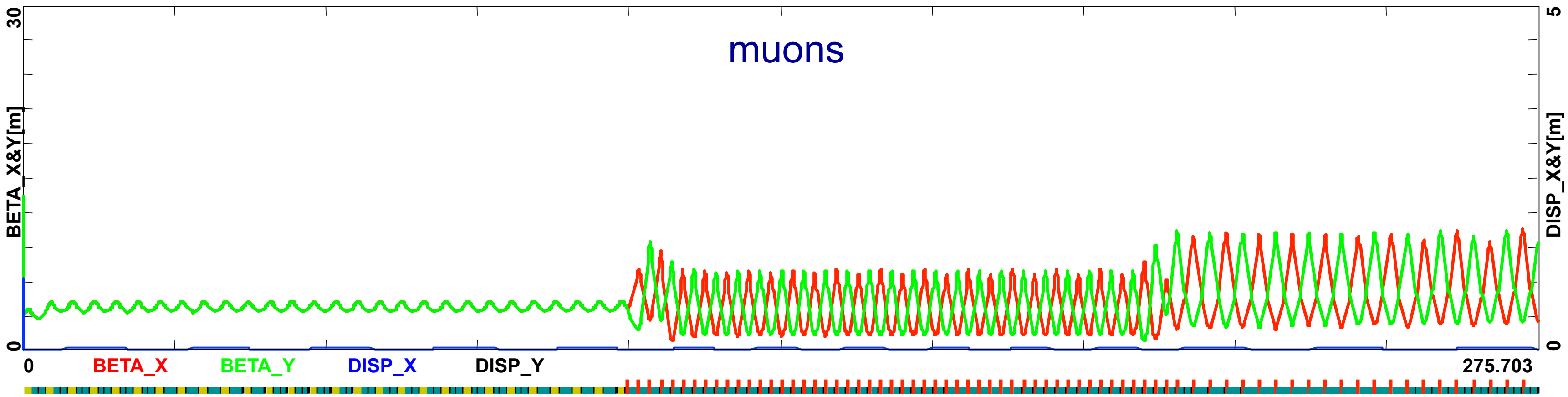


325 MHz muon linac | chicane | 650 MHz dual-use linac

Dual-use Linac – muons vs protons

1.25 GeV

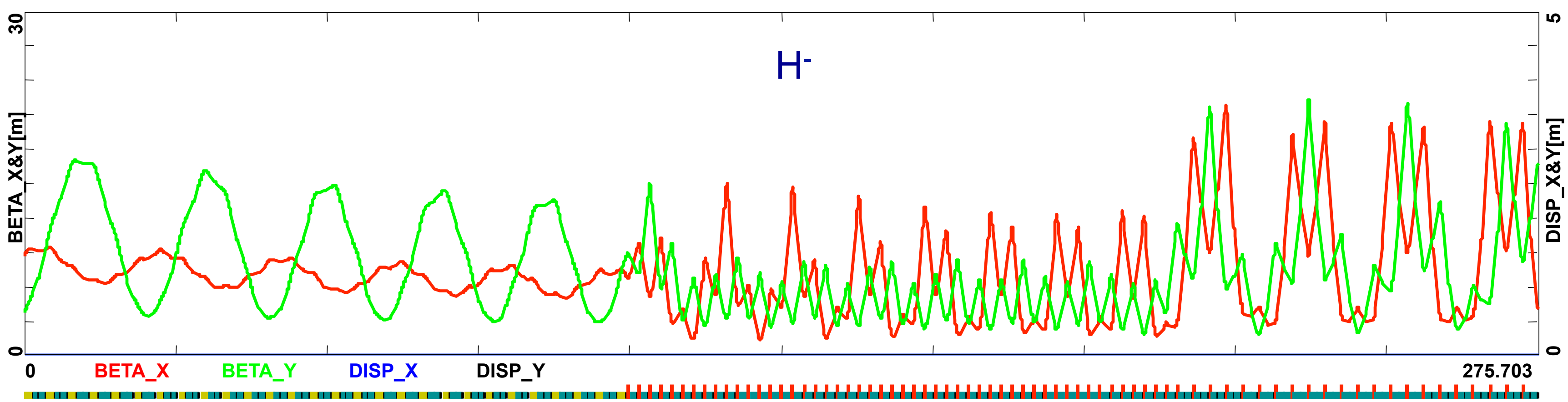
5 GeV



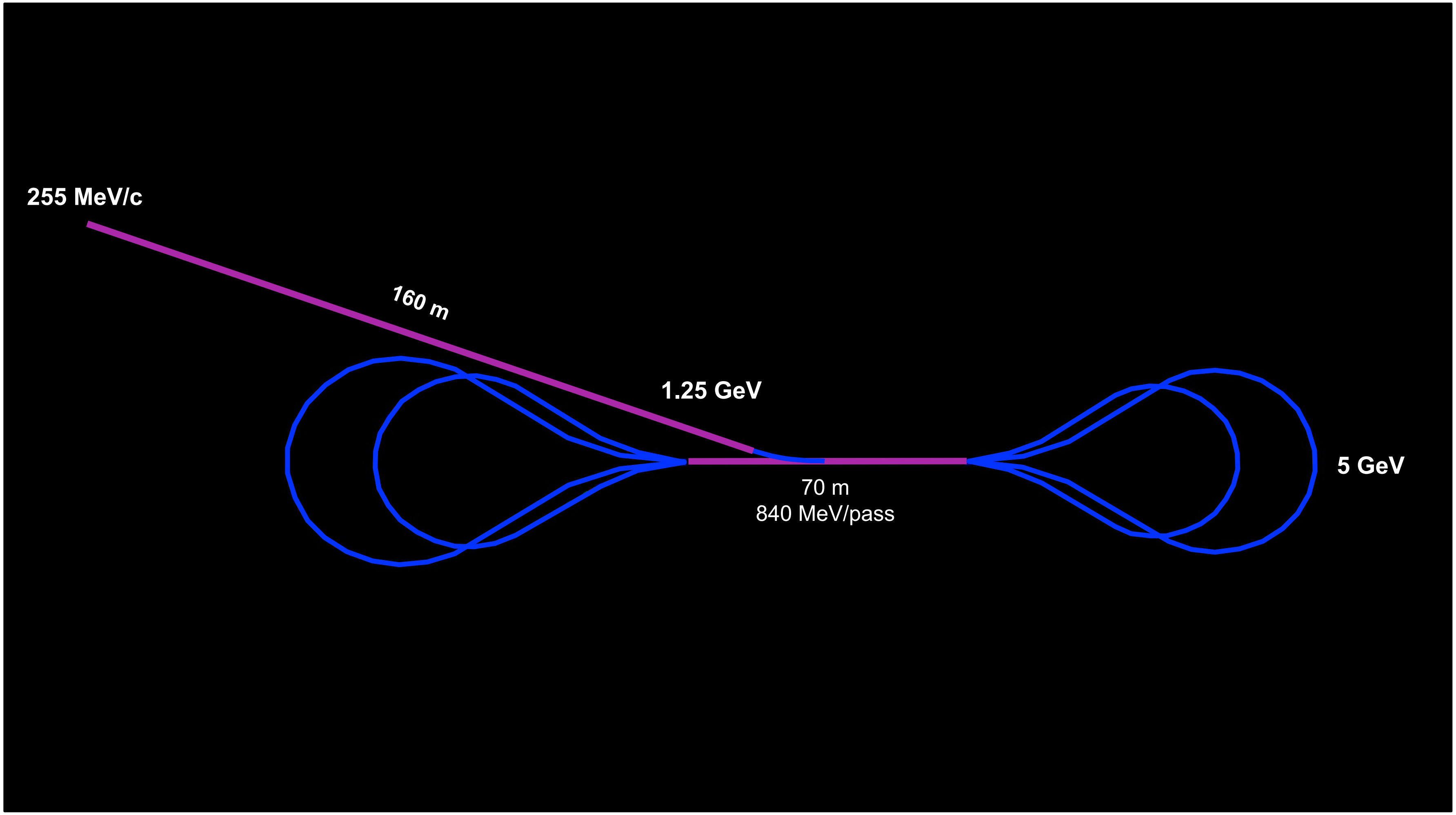
chicane

3 GeV

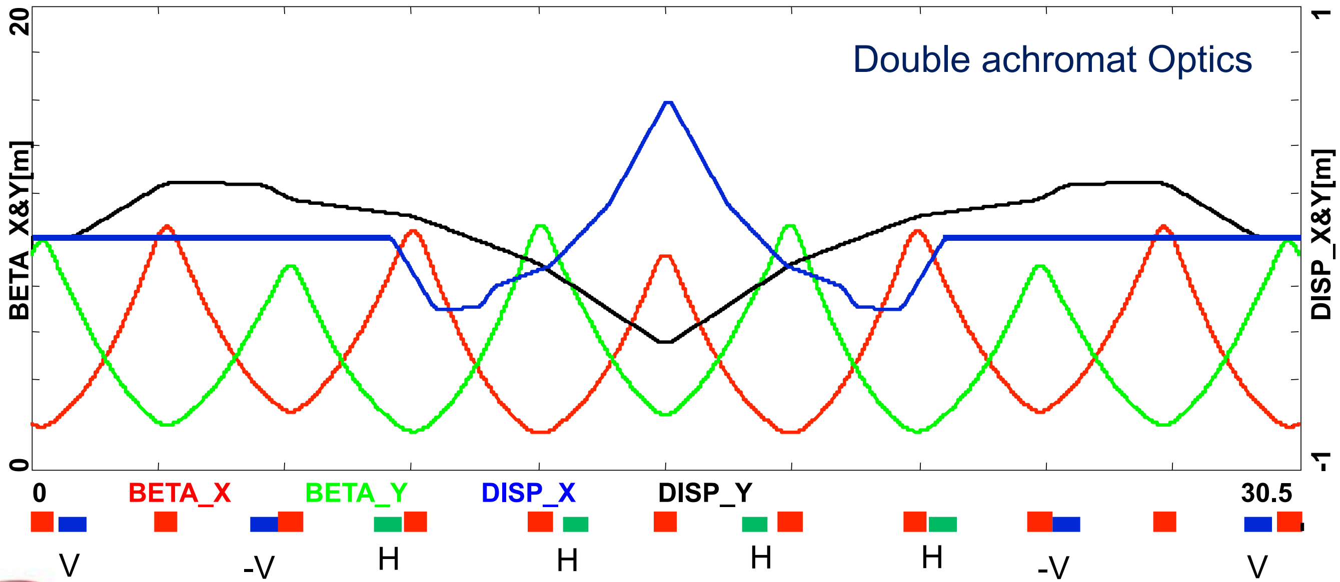
6.8 GeV



Linac and RLA to 5 GeV



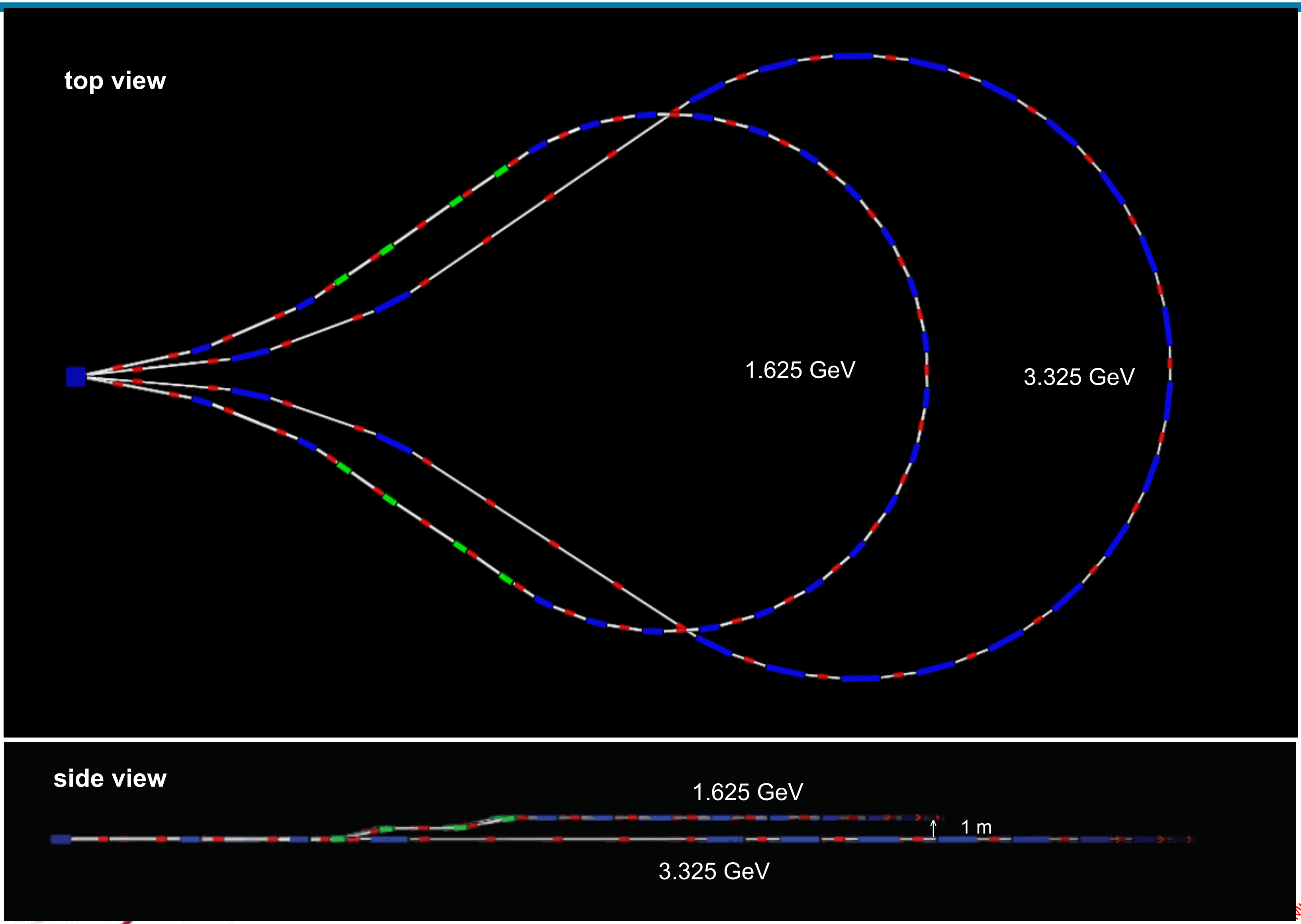
Double Arc Chicane – Optics



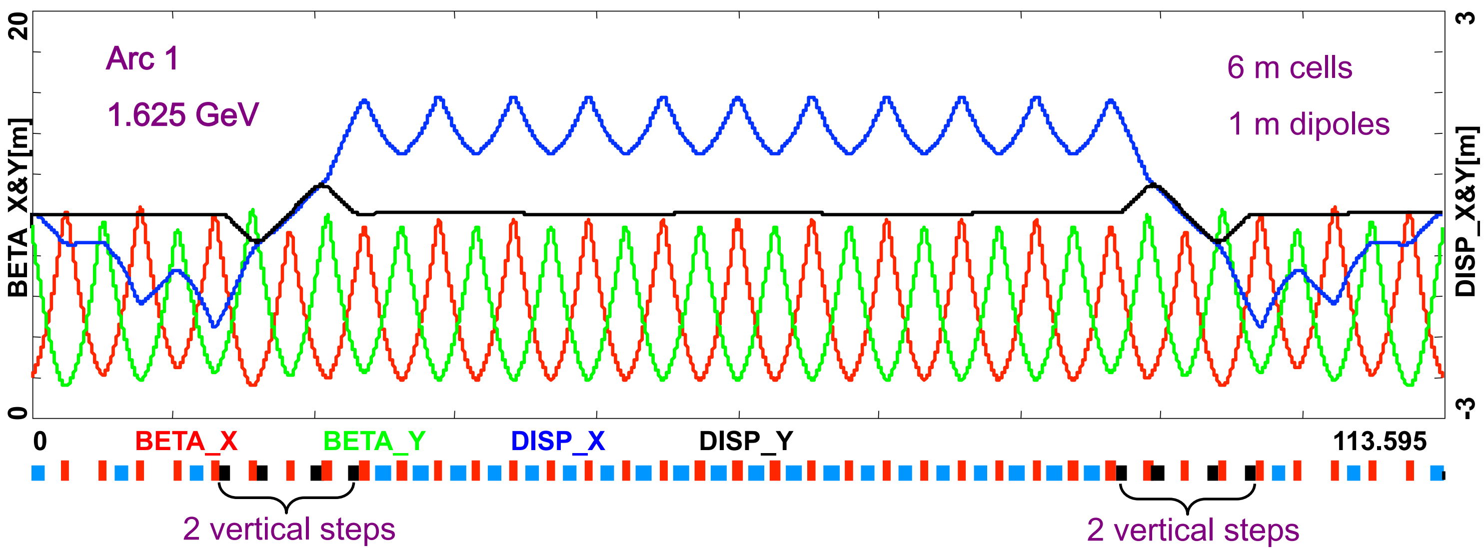
FODO lattice:

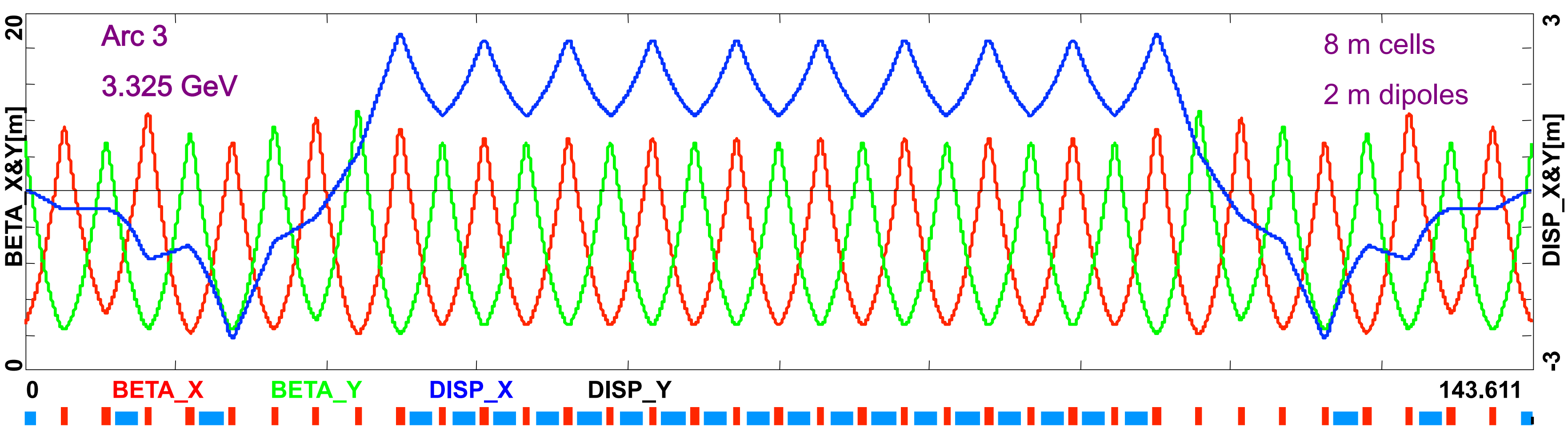
$90^0/90^0$ (h/v) betatron phase adv. per cell

Arc 1 and Arc 3

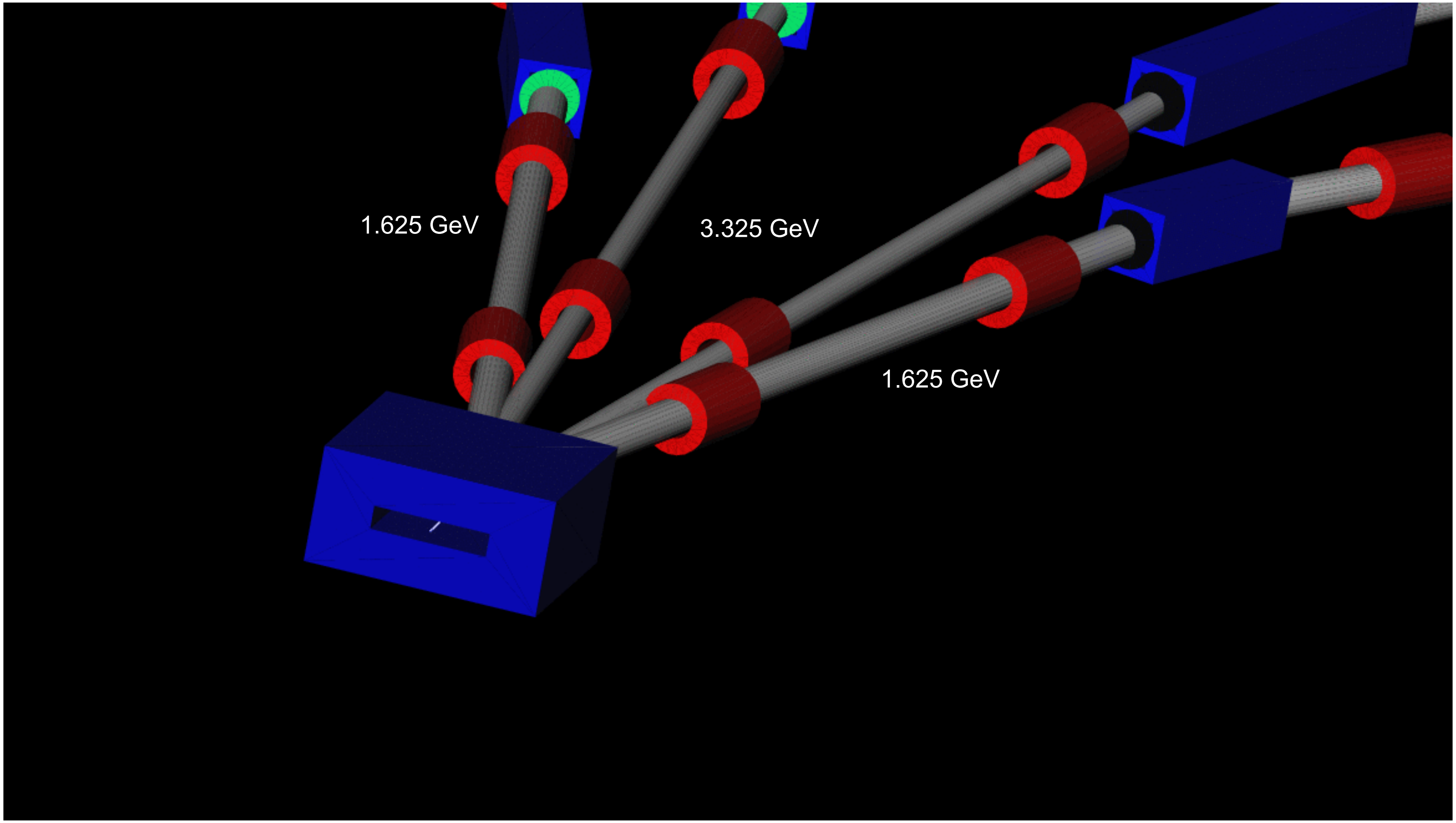


Arc 1 and 3 – Optics



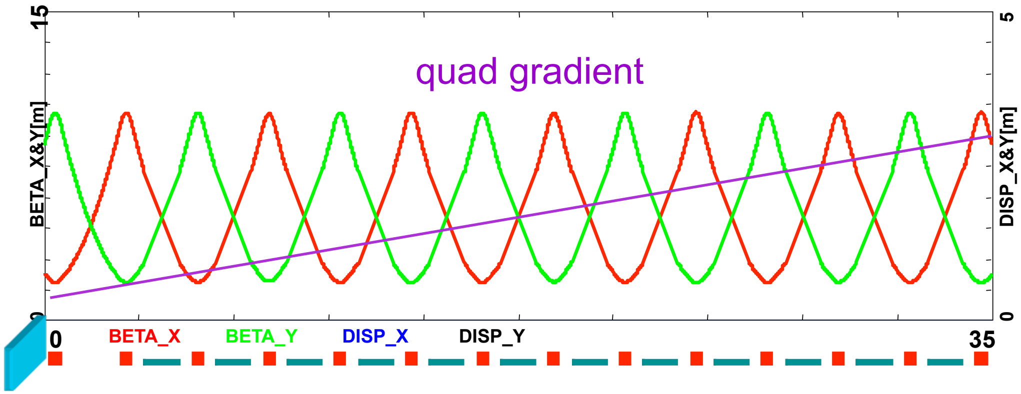


Switchyard – Arc 1 and 3



Bi-sected Linac Optics

'half pass', 1250-1625 MeV

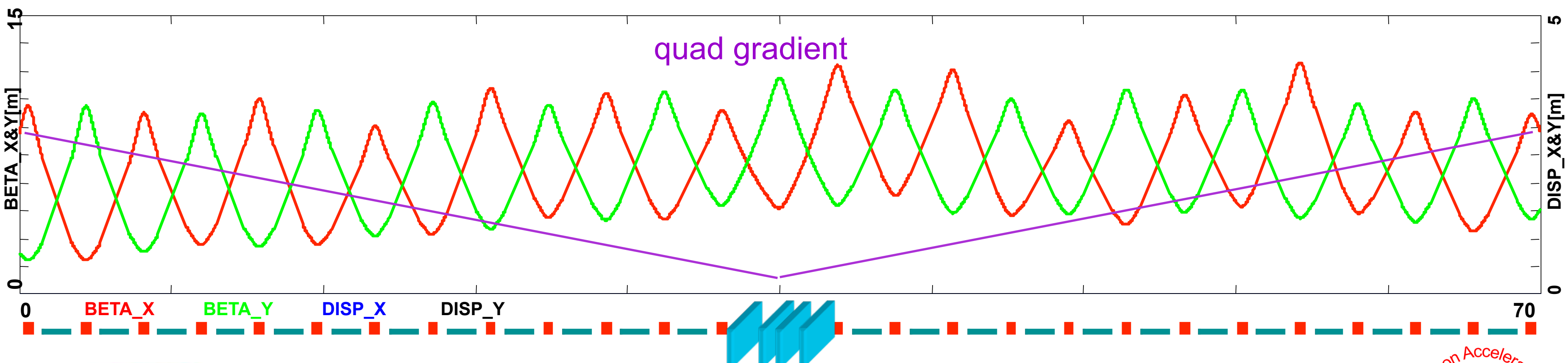


initial phase adv/cell 90 deg. scaling quads with energy

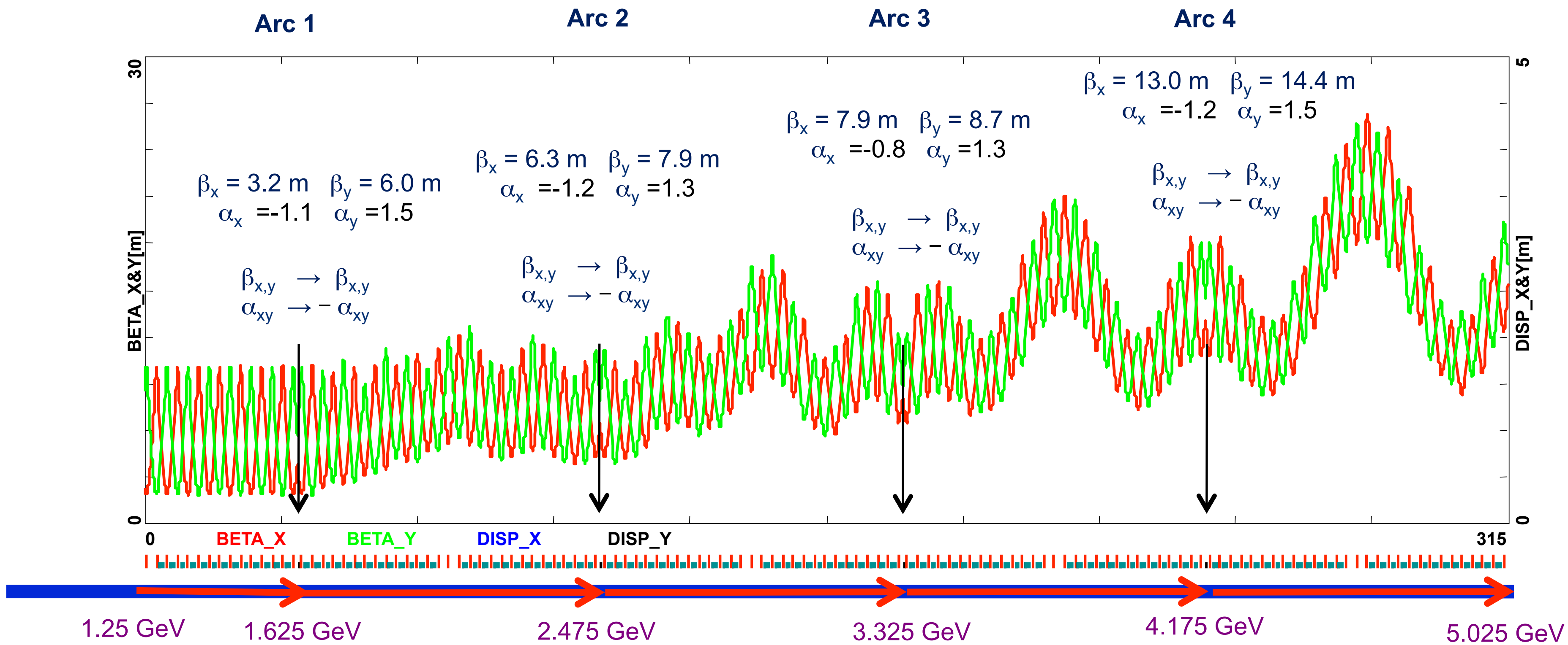
4 meter 90 deg. FODO cells
25 MV/m, 650 MHz, 2×4-cell cavity

1-pass, 1625-2475 MeV

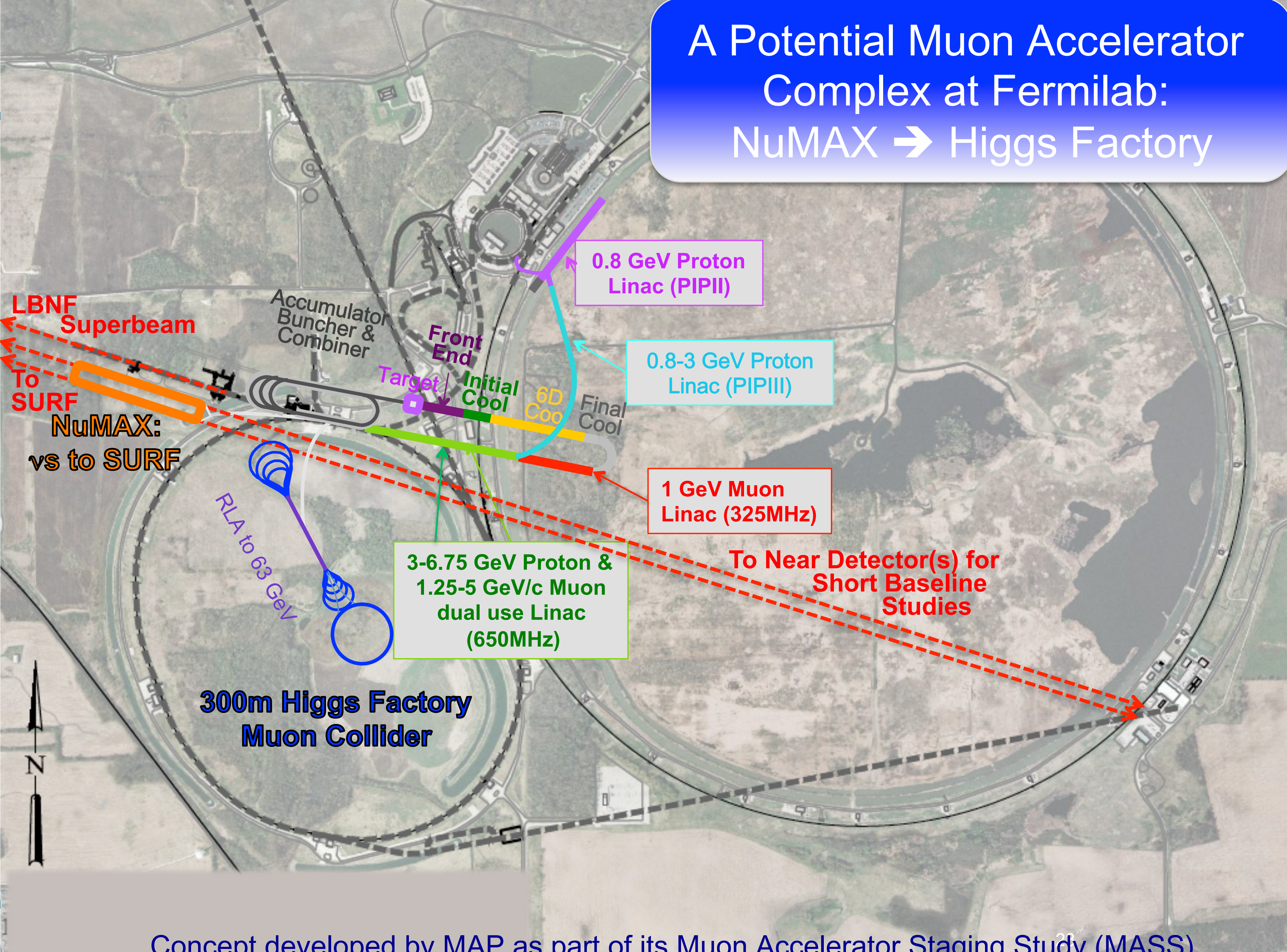
mirror symmetric quads in the linac



Multi-pass Linac Optics



A Potential Muon Accelerator Complex at Fermilab: NuMAX → Higgs Factory



Concept developed by MAP as part of its Muon Accelerator Staging Study (MASS)

Beam Loading

J.S. Berg
J.-P. Delahaye

stored energy in a cavity: $$\frac{V^2}{\omega(R/Q)}$$

fractional reduction in the cavity voltage : $$\frac{\Delta V}{V} = \frac{enN\omega(R/Q)\cos\phi}{V}$$

RF gradient G defined as: $$V = n_C G\pi c/\omega,$$

$$\boxed{\frac{\Delta V}{V} = \frac{enN\omega^2[(R/Q)/n_C]\cos\phi}{\pi G c}}$$

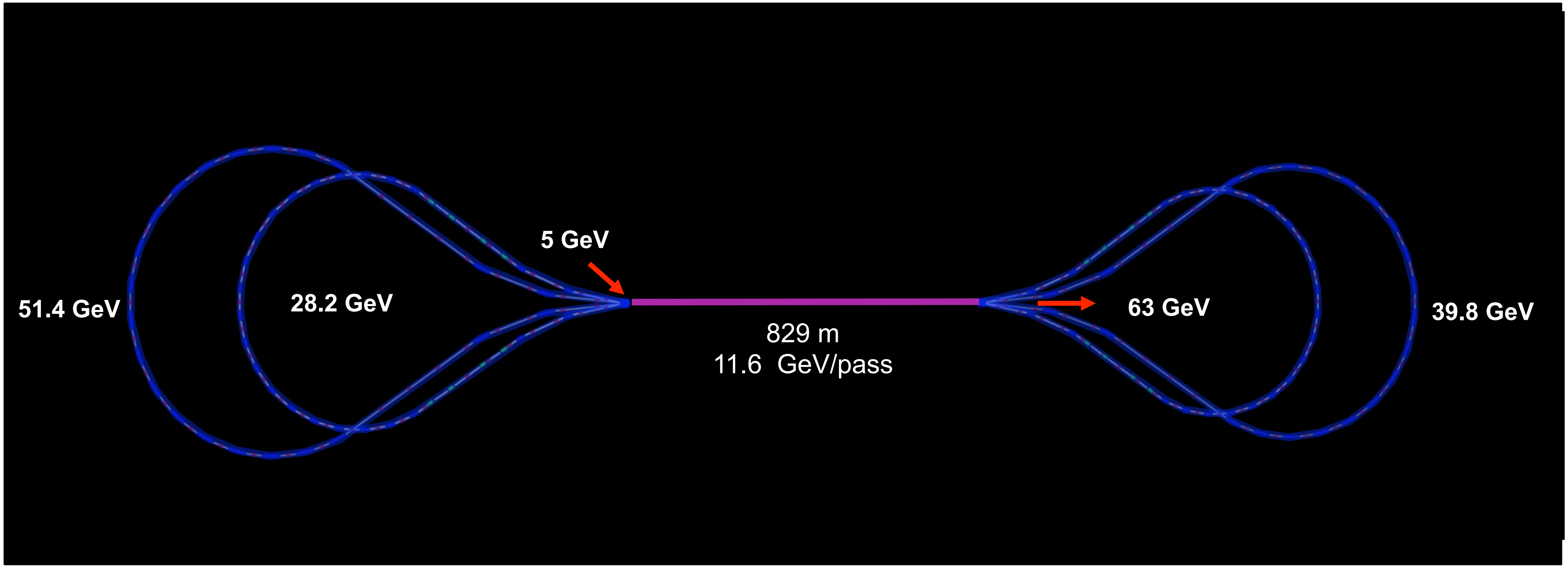
fractional voltage reduction:

$$(R/Q)/n_C = 114\,\Omega$$

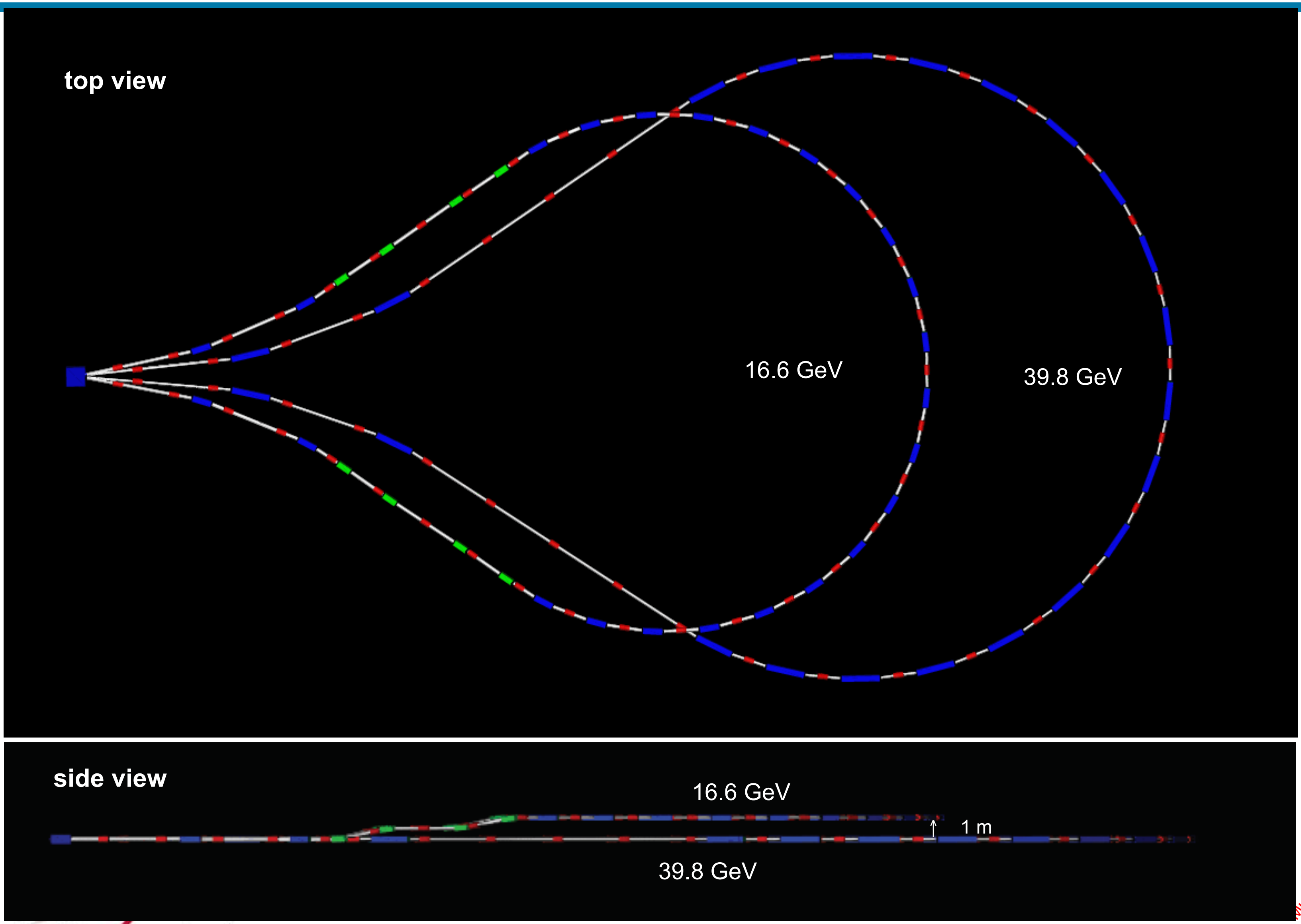
$$\phi = 0$$

Particles	2×10^{12}	4×10^{12}	2×10^{12}	4×10^{12}
Frequency	325 MHz	325 MHz	650 MHz	650 MHz
Passes	Relative reduction (%)			
3	2	5	8	16
5	4	8	13	26
7	6	11	18	36
9	7	15	23	47

5-pass RLA 5–63 GeV

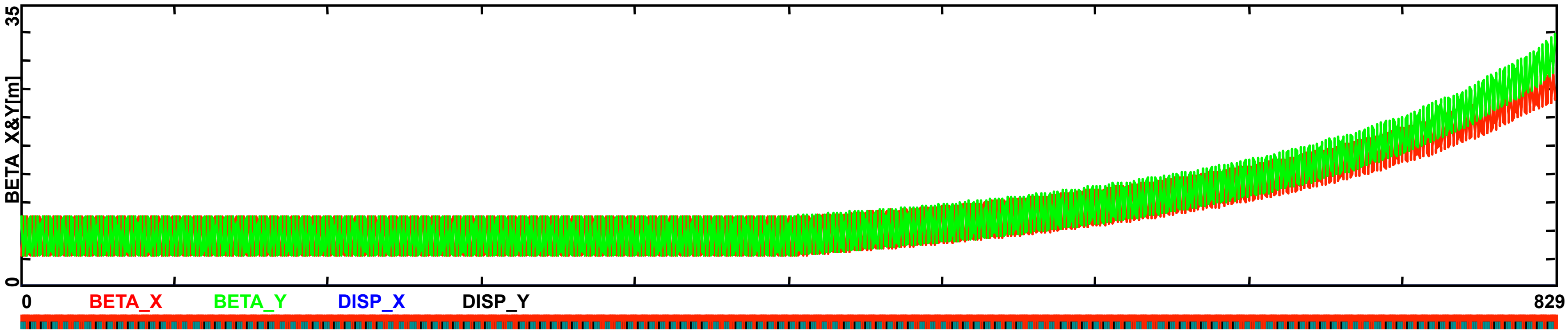


Arc 1 and Arc 3



Linac – Bisected Optics

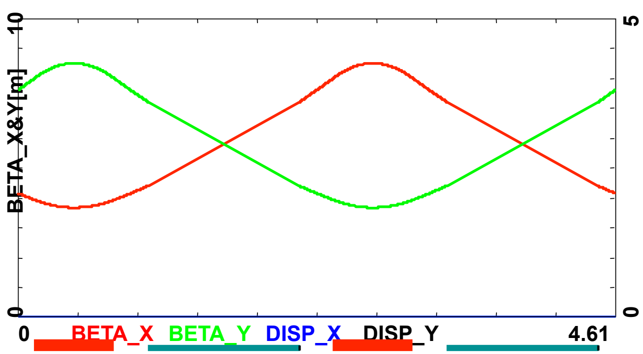
E = 5–16.6 GeV

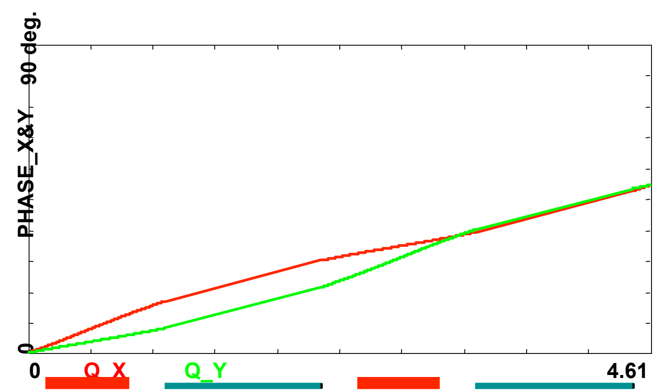


90 cells (quad gradients scaled with momentum)

90 cells (quads reversed in mirror-symmetric pattern)

49^0 FODO

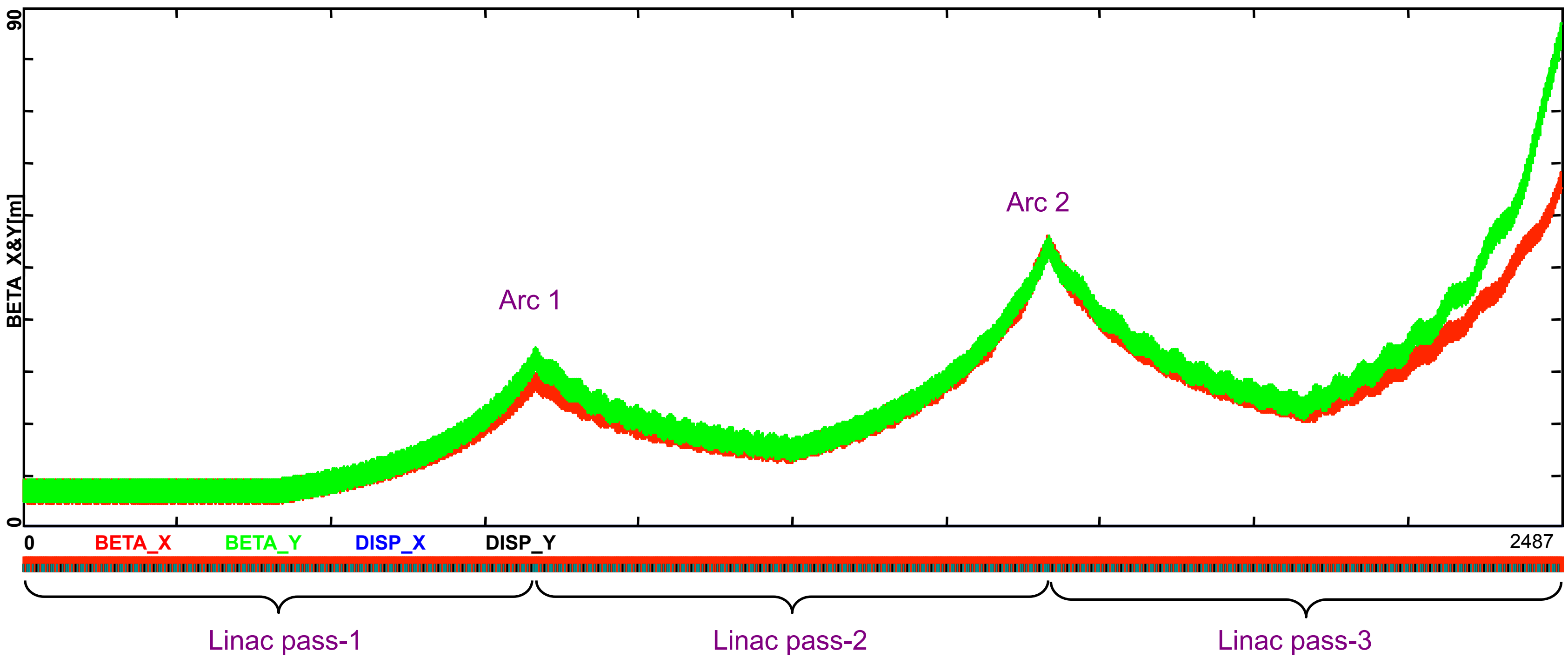




RF	f[MHz]	cells/cavity	Grad [MV/m]	phase [deg]
	650	5	25	22

Multi-pass Linac – Bisected Optics

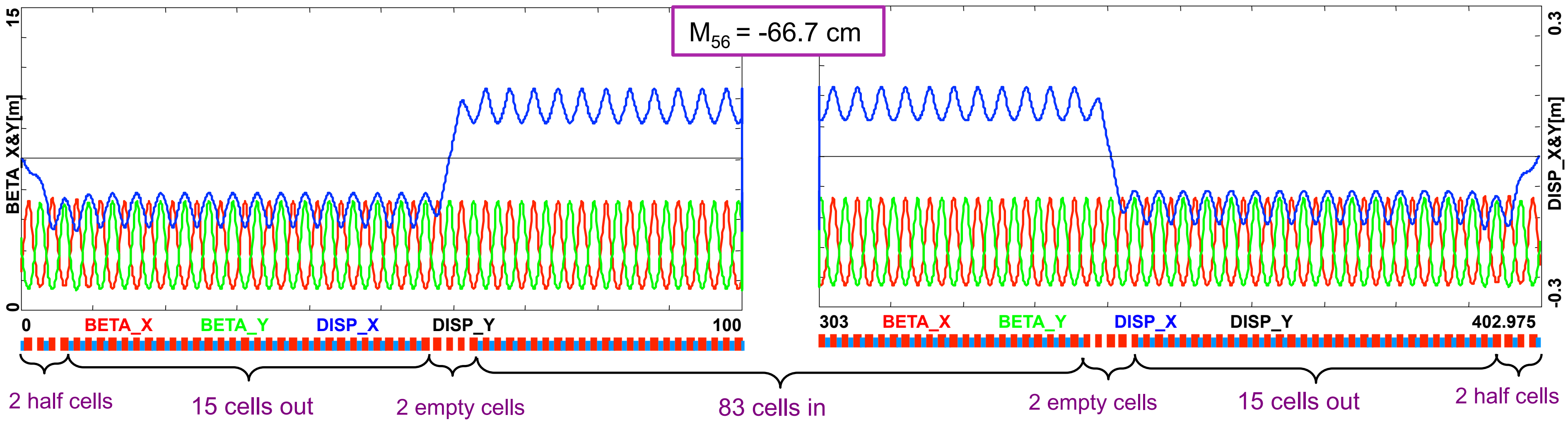
E = 5–63 GeV



RF	f[MHz]	cells/cavity	Grad [MV/m]	phase [deg]
	650	5	25	22

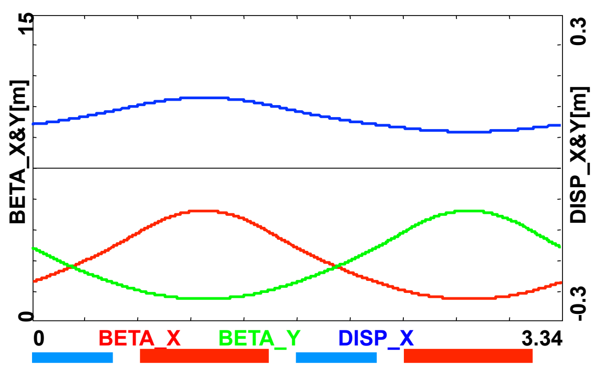
Arc Optics – Longitudinal Distortion

E = 24 GeV



$$n_i = 5n_o + 8$$

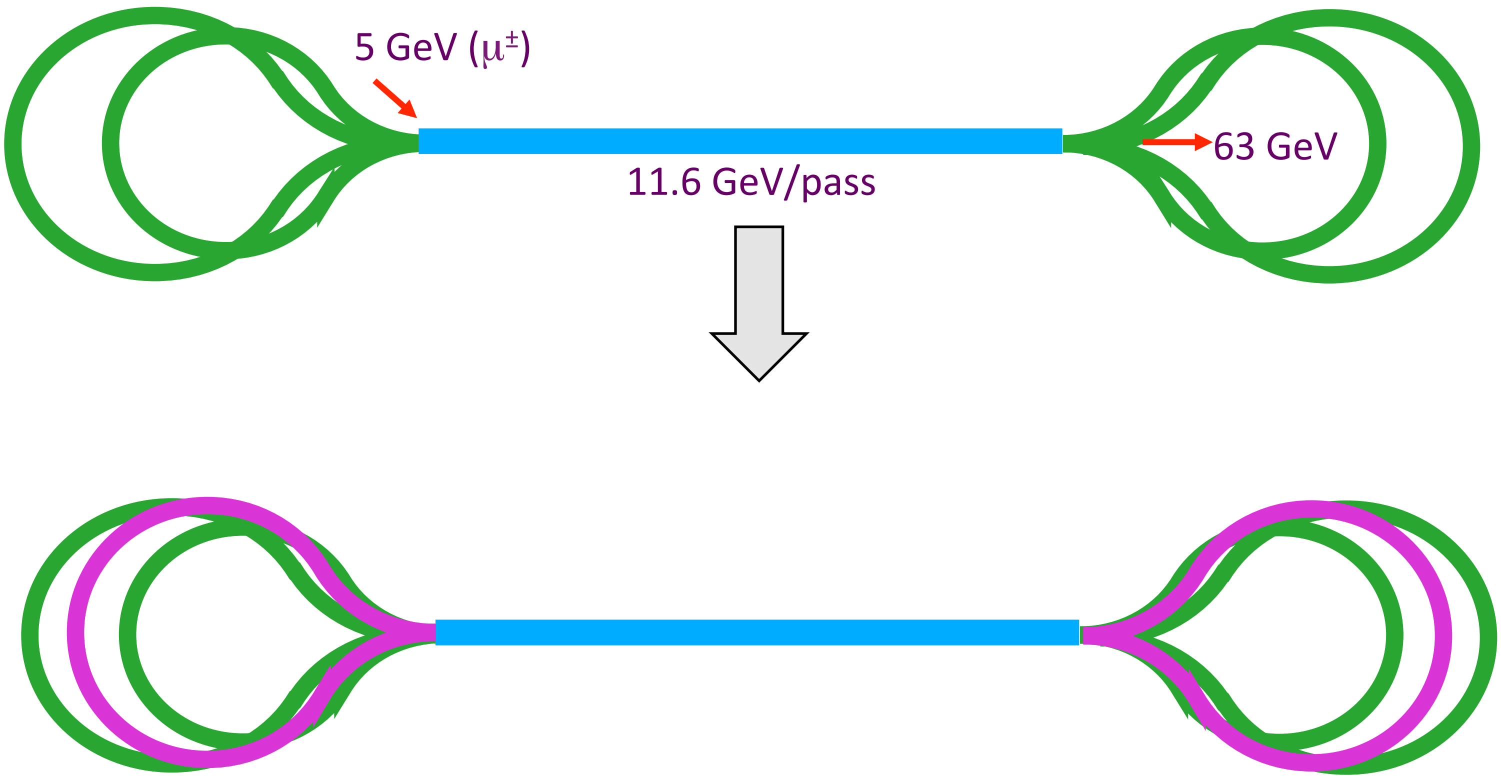
90^0 FODO



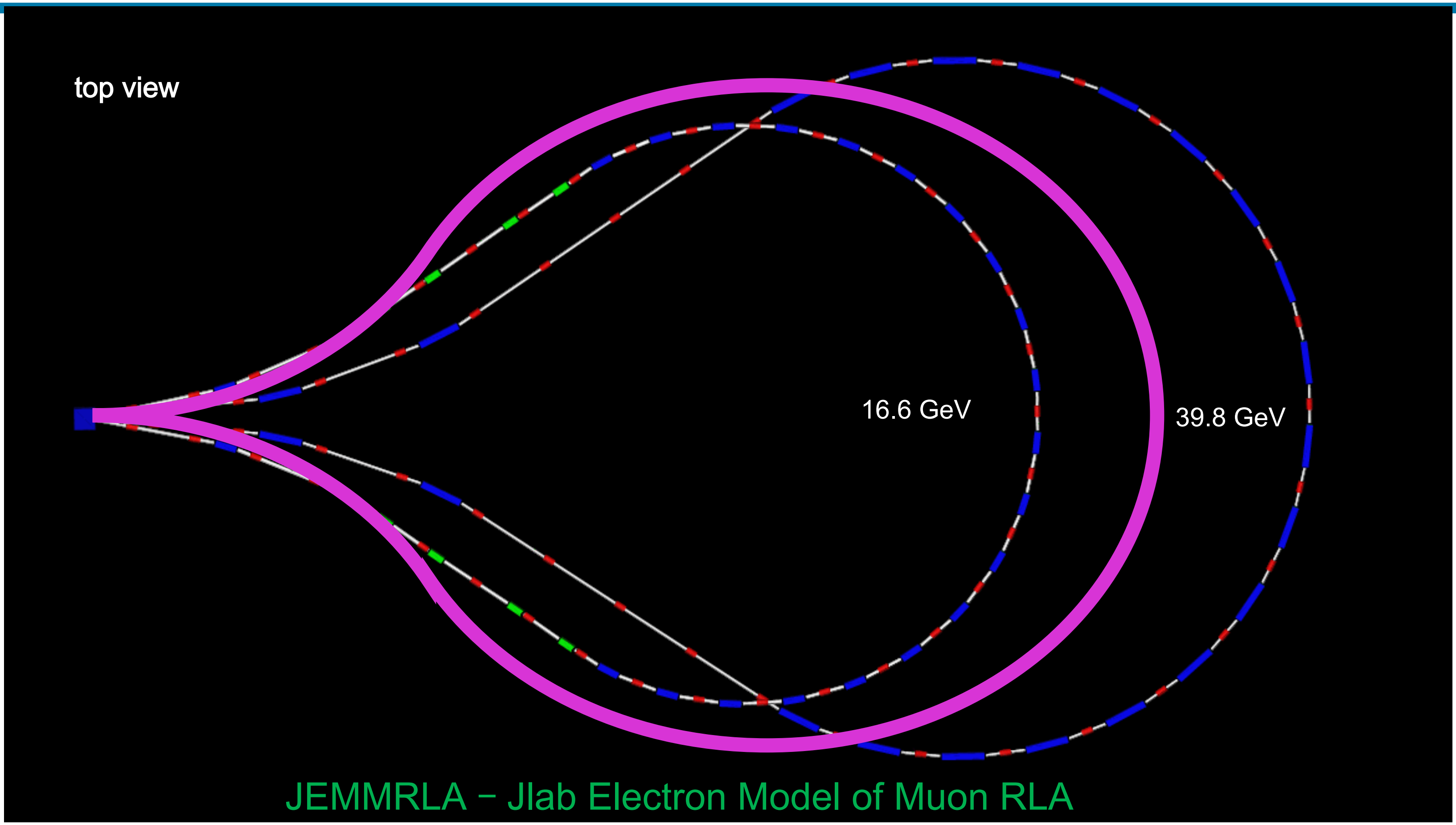
Quads	L[cm]	G[kG/cm]
qF	80	10.2924
qD	80	-10.2788

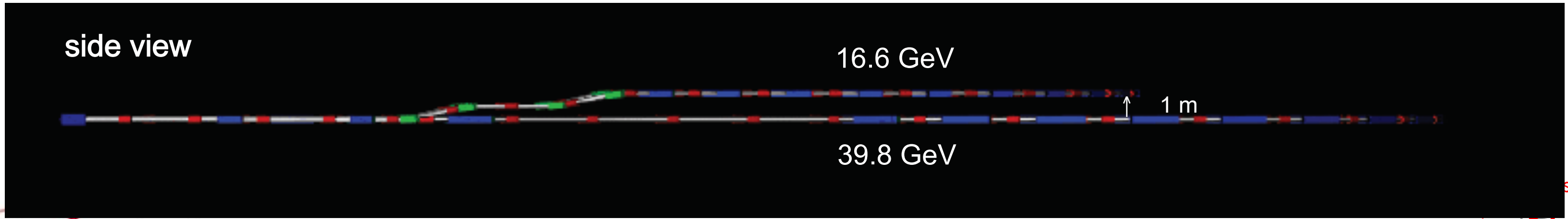
Dipoles	L[cm]	B[kG]	bend angle [deg]
	50.00	49.3116	1.7647

Multi-pass Arc Muon RLA



Single- vs Multi-pass Droplet Arcs





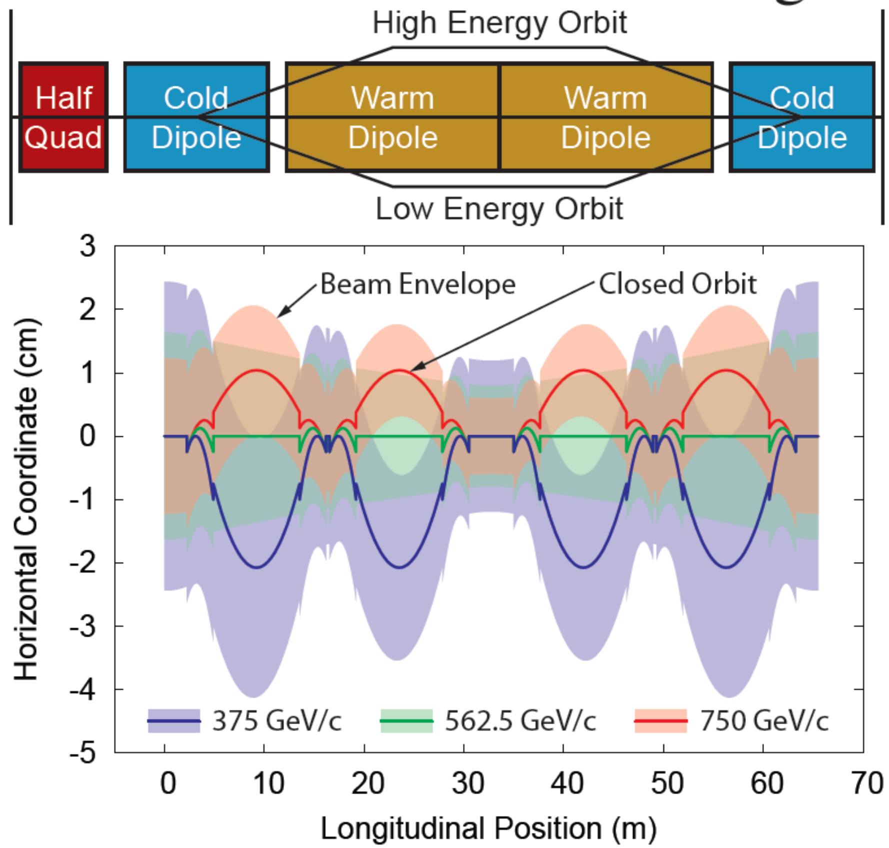
TeV scale MC – Rapid Cycling Synchrotron

- Pulse a synchrotron very rapidly as beam accelerates
- First proposed by Summers in 1996
- Permits maximal passes through RF cavities with modest apertures
- Field of pulsed magnets must be generated by iron
- Would like a higher average bend field
- Interleave superconducting fixed-field and bipolar pulsed dipoles
- Acts like a dipole with average field $(B_C L_C + B_W L_W)/(L_C + L_W)$

J.S. Berg

Rapid Cycling Synchrotrons

- Beam will not remain centered in magnets



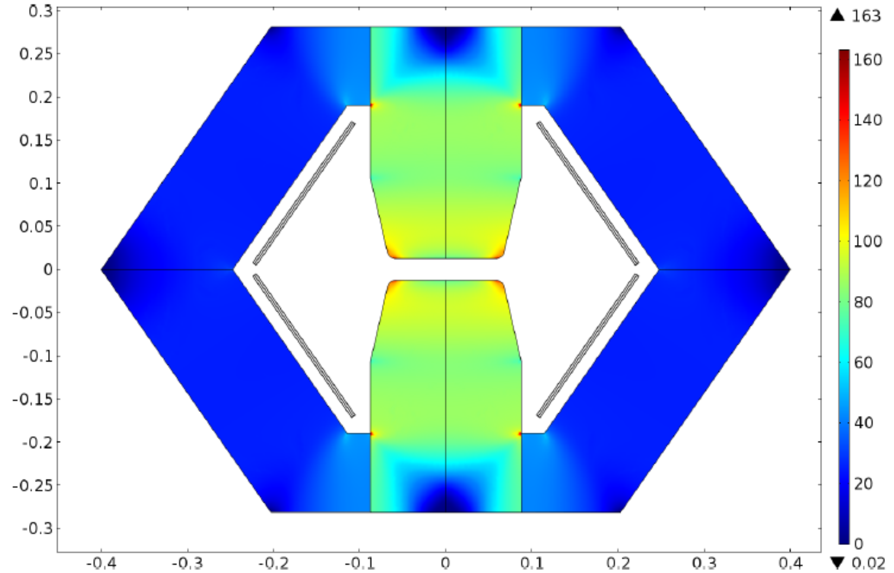
Magnets: 10 T fixed, 1.5 T pulsed

Hybrid	$p_{\min}$ GeV/c	$p_{\max}$ GeV/c	Time ms	Turns
No	63	375	0.3	10
Yes	63	173	0.1	18
Yes	173	375	0.2	18
Yes	375	750	0.4	18
Yes	750	1500	0.8	18

J.S. Berg

Pulsed Magnets

- Holger Witte: two-material pulsed magnet design
  - Low-loss material in back yoke
  - High saturation material for pole
  - Takeaway: pulsed magnet designs possible with non-oriented materials and acceptable losses



Summary

- Conceptual schemes for 5 GeV Neutrino Factory (a la NuMAX)
  - Scheme I - SRF efficient design based on multi-pass Dogbone RLA
    - Linac (255 MeV – 1.25 GeV) Longitudinal compression
    - Delay/Compression Chicane – Transition from 325 to 650 MHz SRF
    - RLA (1.25 – 5 GeV) 4 droplet Arcs and multi-pass linac
  - Scheme II – Conceptual design based on dual-use (H^- and muons) linac. Further compatibility studies on:
    - H^- dynamics in a strongly focusing solenoid based FOFO channel, e.g. effect of solenoid fringe fields on H^- ion stripping
- Optimized RLA scheme for Higgs Factory and beyond (MC):
  - Number of passes limited by beam loading
  - RLA with multi-pass arcs
  - TeV scale acceleration – Rapid Cycling Synchrotrons